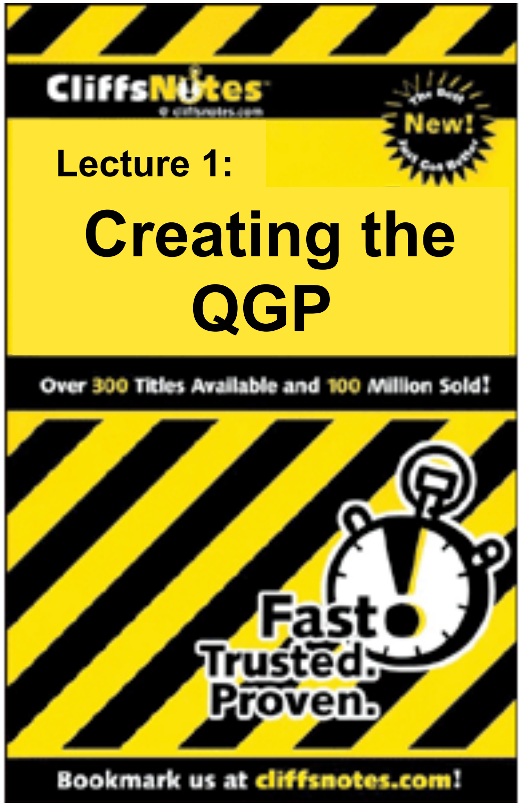
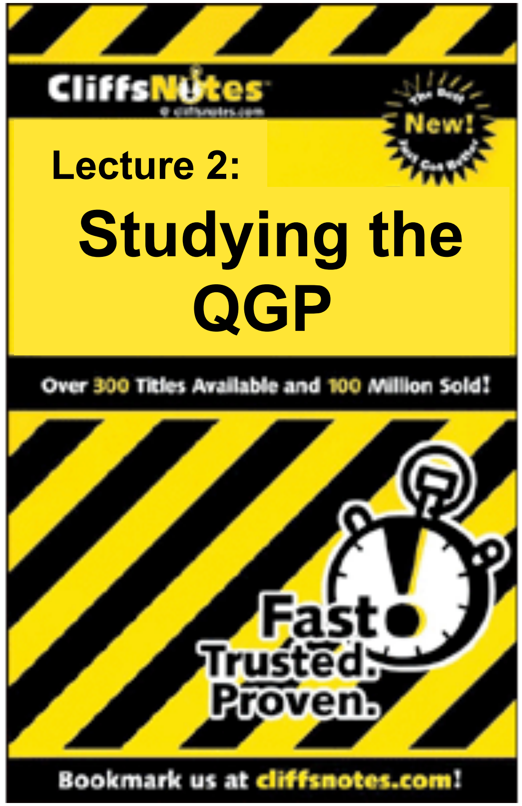
Studying a new Phase of Matter - An introduction to the Quark Gluon Plasma and Relativistic Heavy Ion Physics





2010 Hadron Collider Physics Summer School

Fermi Lab - August 2010

Helen Caines - Yale University

Relativistic Heavy Ions I - The What, Where, Why, and How of It All

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Outline :

QCD and Asymptotic Freedom

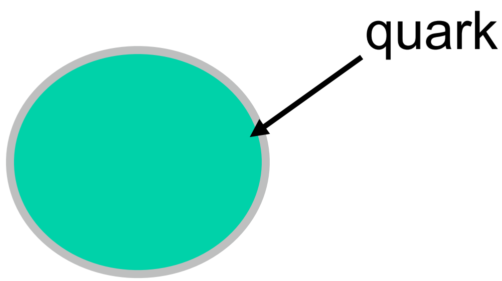
The Quark Gluon Plasma

The Accelerators & Experiments

Evidence for the QGP

Confinement - QCD

Confinement: fundamental & crucial feature of strong interaction
force = const has significant consequences



"white" proton

Confinement - QCD

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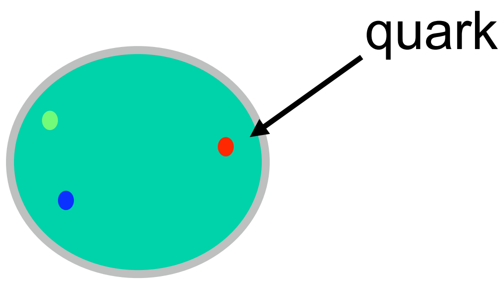

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Confinement - QCD

Confinement: fundamental & crucial feature of strong interaction
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Strong **color** field
Force *grows* with
separation !!!

Confinement - QCD

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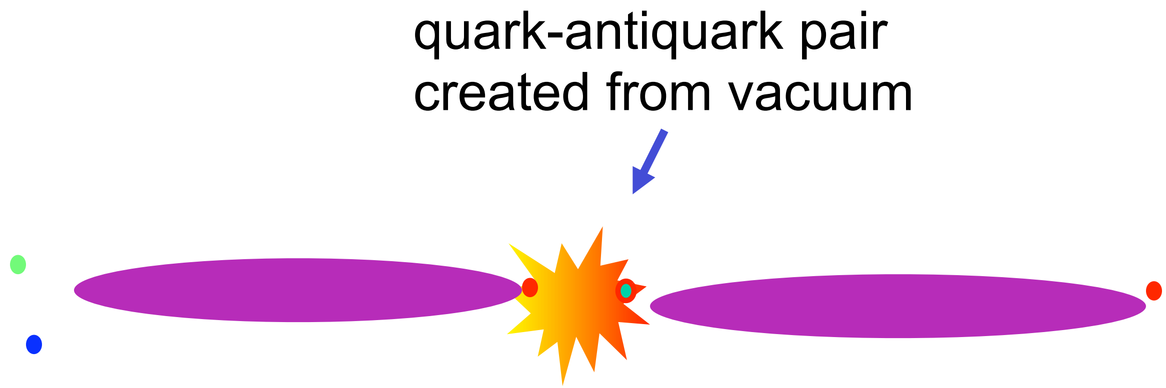

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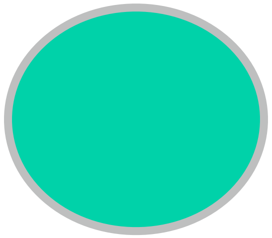
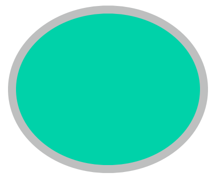


"white" proton
(confined quarks)



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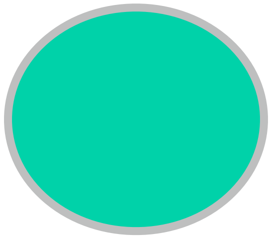

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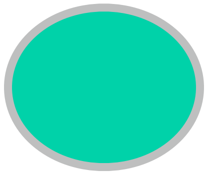

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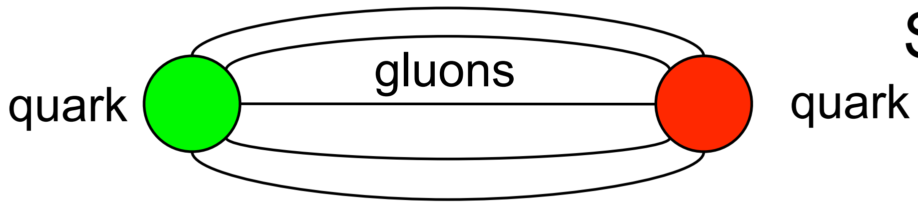
To understand the strong force and confinement: Create and study a system of deconfined colored quarks and gluons

We don't see free quarks



Strong force becomes a constant at ~size of a hadron which is ~1 fm (10^{-15} m)

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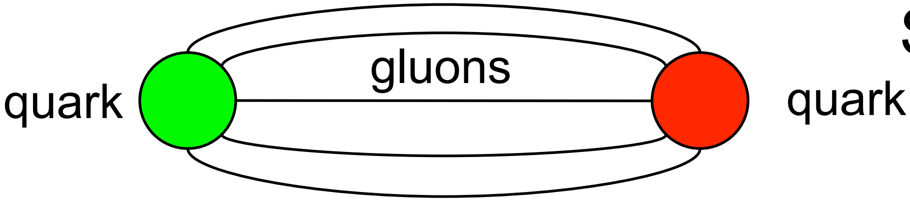

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$$1\,\frac{GeV}{fm} = \frac{10^{9}eV}{10^{-15}m} \times \frac{1.6\times10^{-19}J}{eV} = 1.6\times10^{5}N$$

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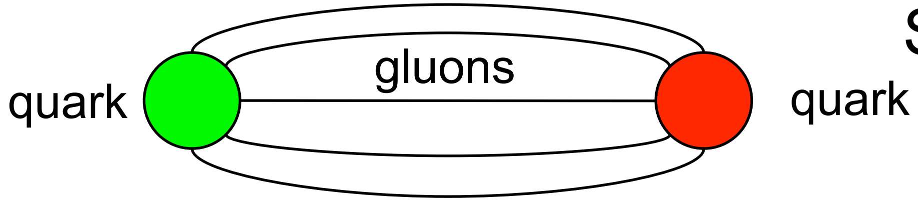

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Compare to gravitational force at Earth's surface

$$F = 1.6 \times 10^5 N = M \times g = M \times 9.8 m/s^2$$

$$\Rightarrow \quad M = 16,300 kg$$

Quarks exert 16 metric tons of force on each other!

Asymptotic freedom

Coupling constant is not a “constant”

Runs with Q^2 (mtm transfer)
accounts for vacuum polarisation

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{[1 + (\alpha_s(\mu^2)\frac{(33-2n_f)}{12\pi})ln(Q^2/\mu^2)]}$$

$\alpha_s(\mu^2) \sim 1$!!
μ^2: renormalization scale
33: gluon contribution
n_f: # quark flavours

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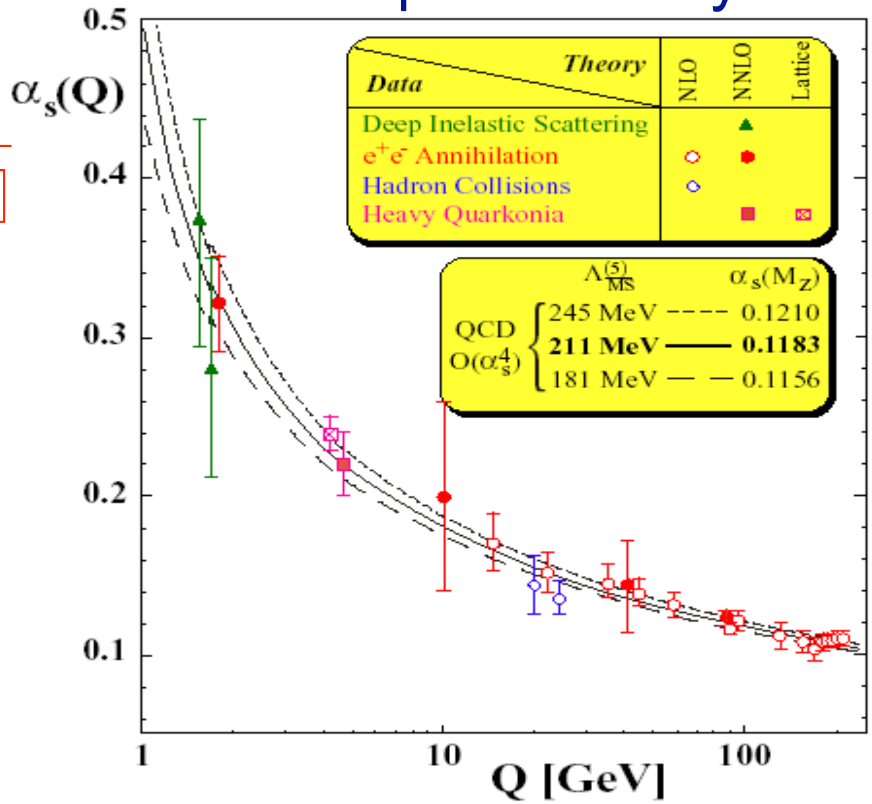
Running measured experimentally



0.2 fm 0.02 fm 0.002 fm

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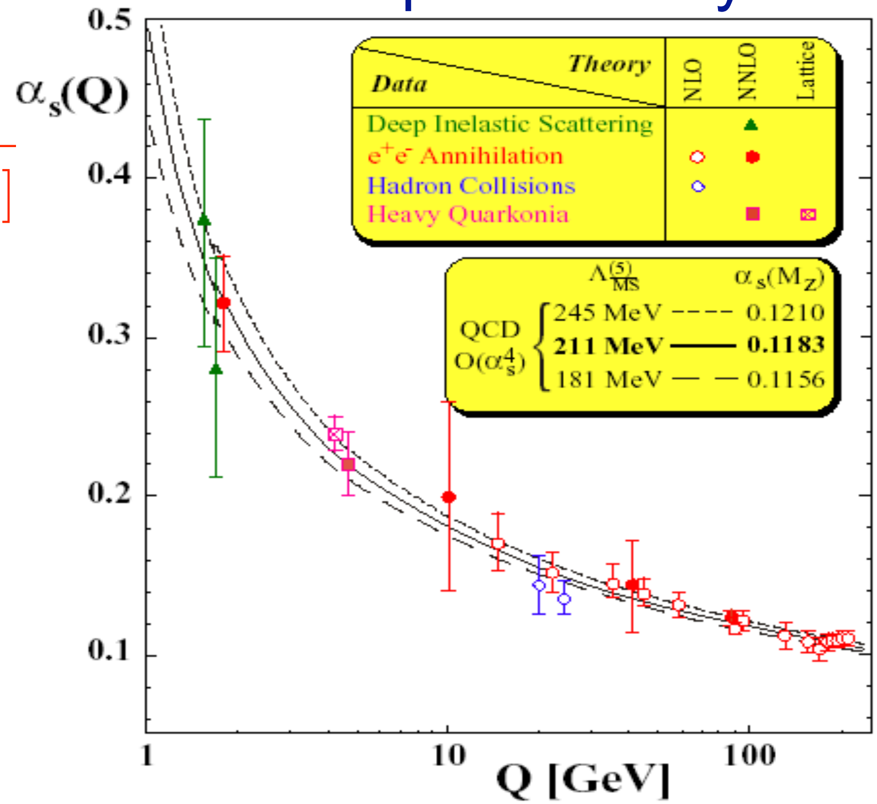


0.2 fm 0.02 fm 0.002 fm

$\alpha_s(Q^2) \rightarrow 0$, as $Q \rightarrow \infty$, $r \rightarrow 0$
Coupling very weak
$\rightarrow$ partons are essentially free

Asymptotic Freedom

Asymptotic freedom

Coupling constant is not a “constant”

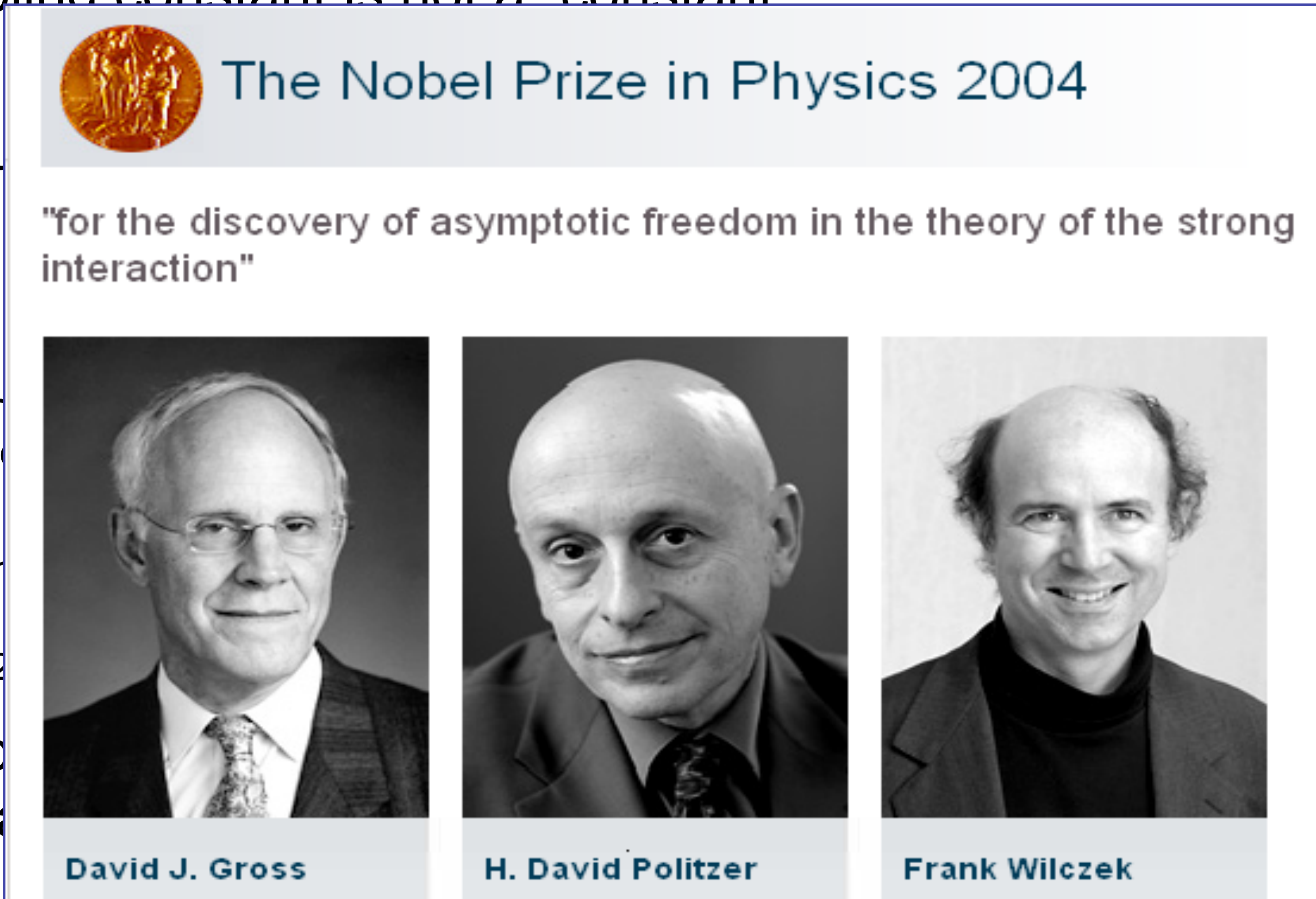
Runs ... ured

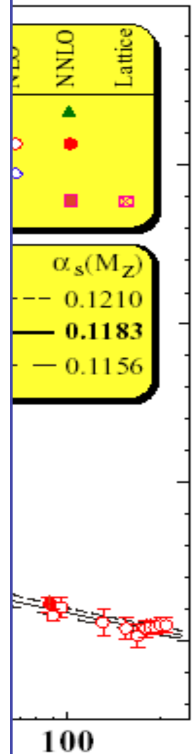
accou ... lly

$\alpha_s(Q^2)$

$\alpha_s(\mu^2)$ ...
μ^2: ren...
33: glu...
n_f: # qu...

$\alpha_s(Q^2$ ...
Coup...
$\rightarrow$ p...





Asymptotic Freedom

0.2 fm 0.02 fm 0.002 fm

Asymptotic freedom vs Debye screening

Asymptotic freedom occurs at very high Q^2

Problem: Q^2 much higher than available in the lab.

So how to create and study this new phase of matter?

Solution: Use effects of Debye screening

In the presence of many colour charges (charge density n), the short range term of the strong potential is modified:

Charges at long range ($r > r_D$) are screened

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In the presence of many colour charges (charge density n), the short range term of the strong potential is modified:

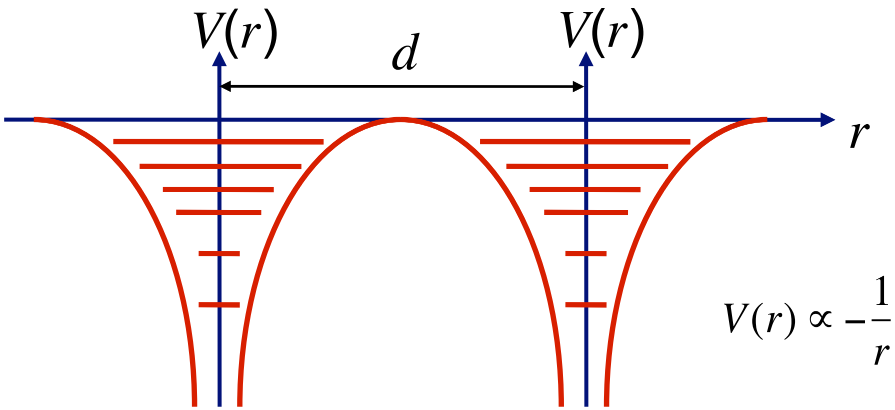
$$V_s(r) \propto \frac{1}{r} \Longrightarrow \frac{1}{r} exp[\frac{-r}{r_D}]$$

where $r_D = \frac{1}{\sqrt[3]{n}}$ is the Debye radius

Charges at long range ($r > r_D$) are screened

QED and Debye screening

$r > r_D$



In condensed matter this leads to an interesting transition

e^- separation > e^- binding radius
→ insulator

$r < r_D$

QED and Debye screening

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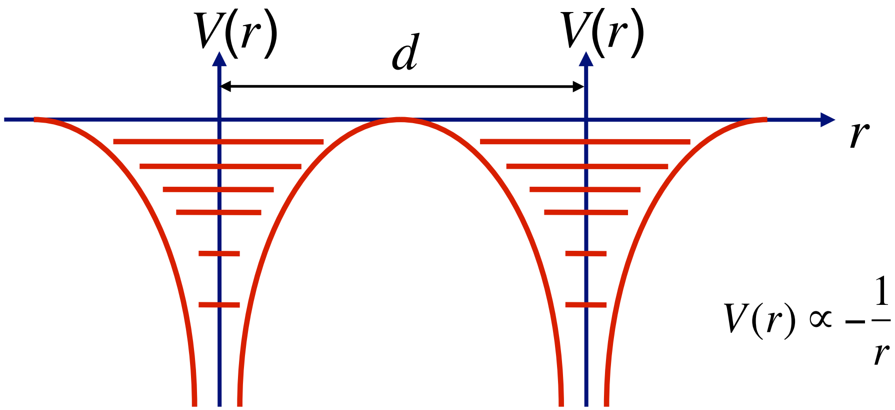

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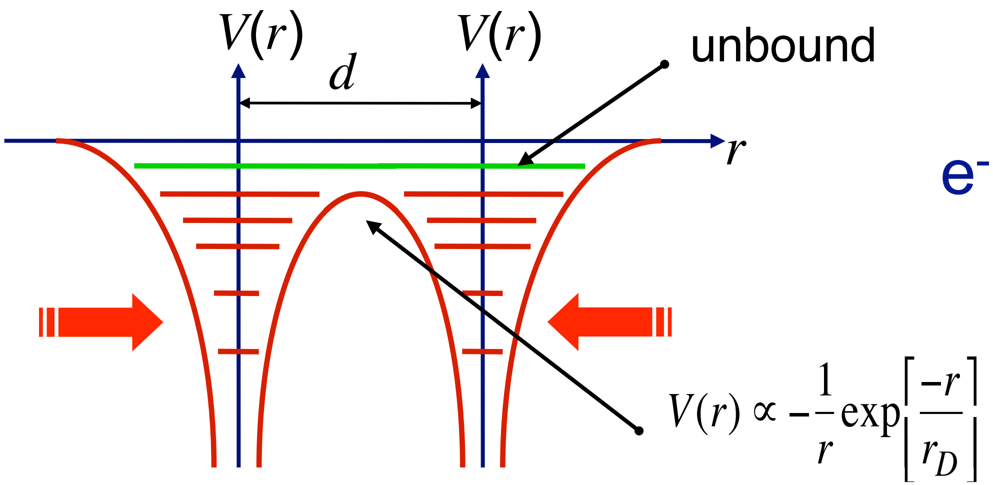


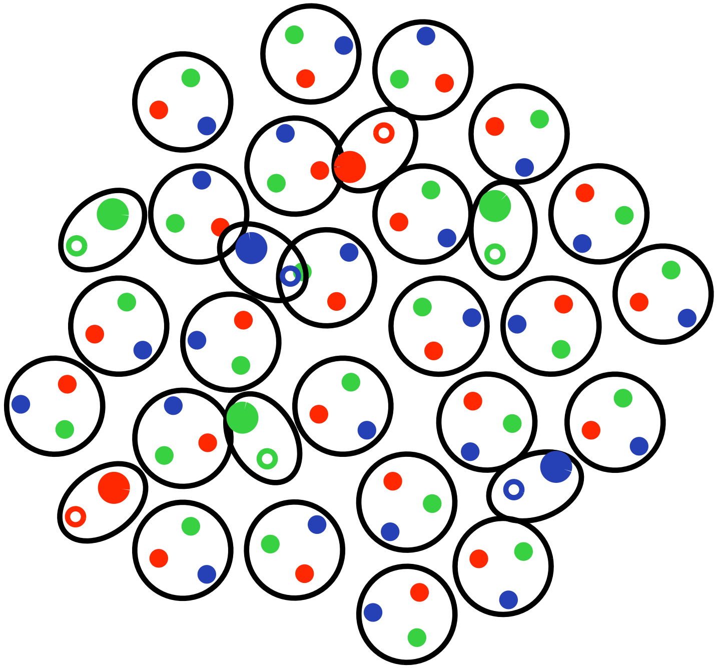
e^- separation < e^- binding radius
→ conductor

This is the Mott Transition

QCD and Debye screening

At low colour densities:

quarks and gluons confined into colour singlets
→ hadrons (baryons and mesons)



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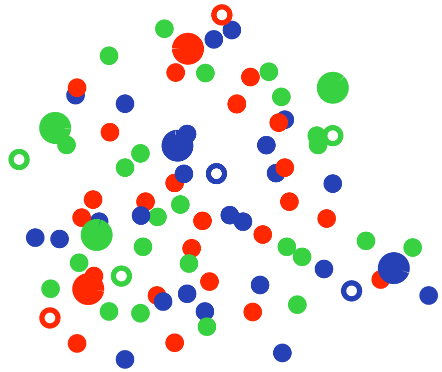

At high colour densities:

quarks and gluons unbound
Debye screening of colour charge

→ QGP - colour conductor

QCD and Debye screening

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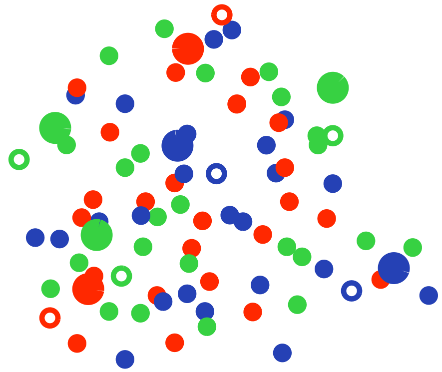

At high colour densities:

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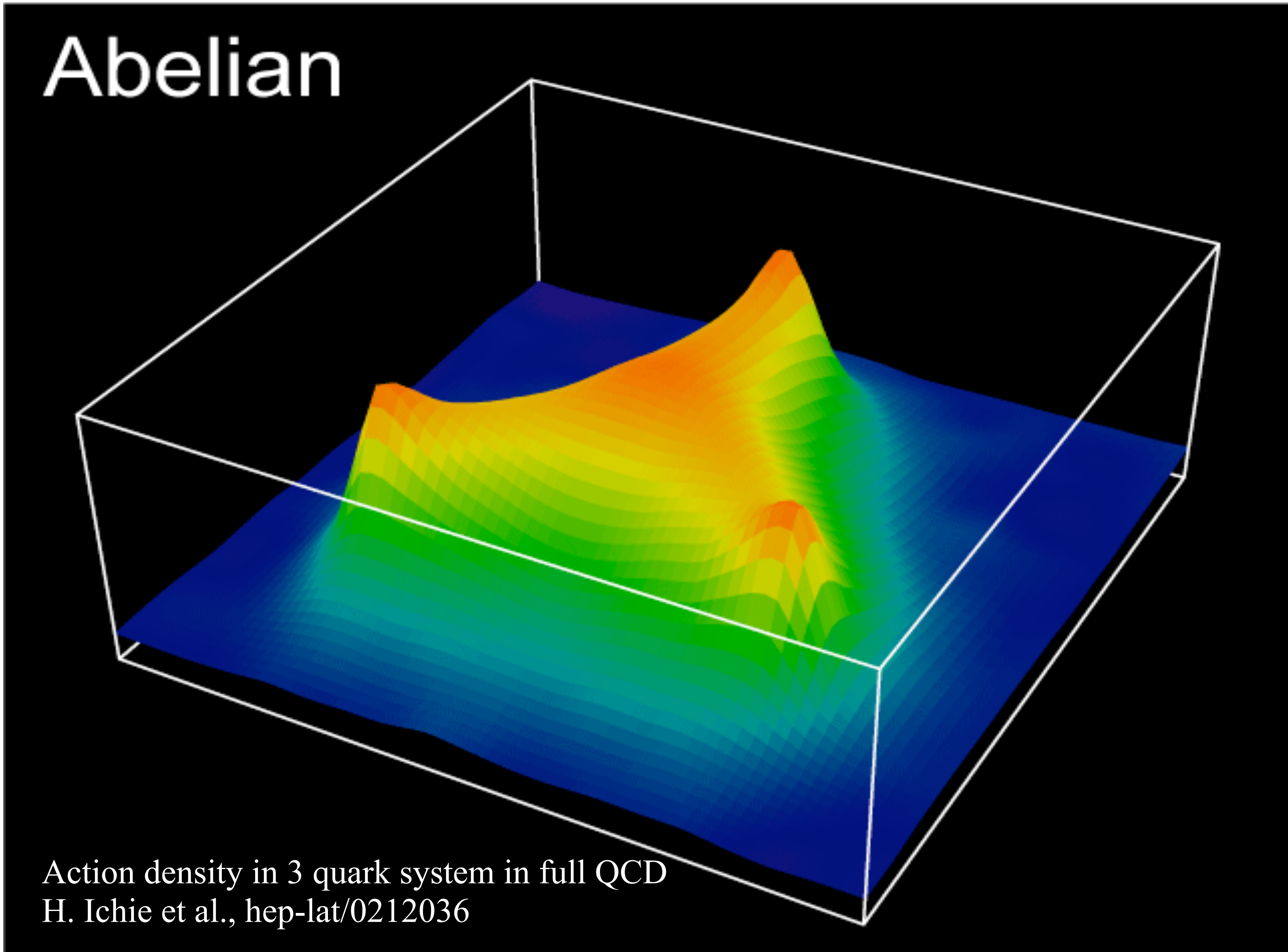
→ QGP - colour conductor

Can create high colour density by heating or compressing

→ QGP creation via accelerators or in neutron stars

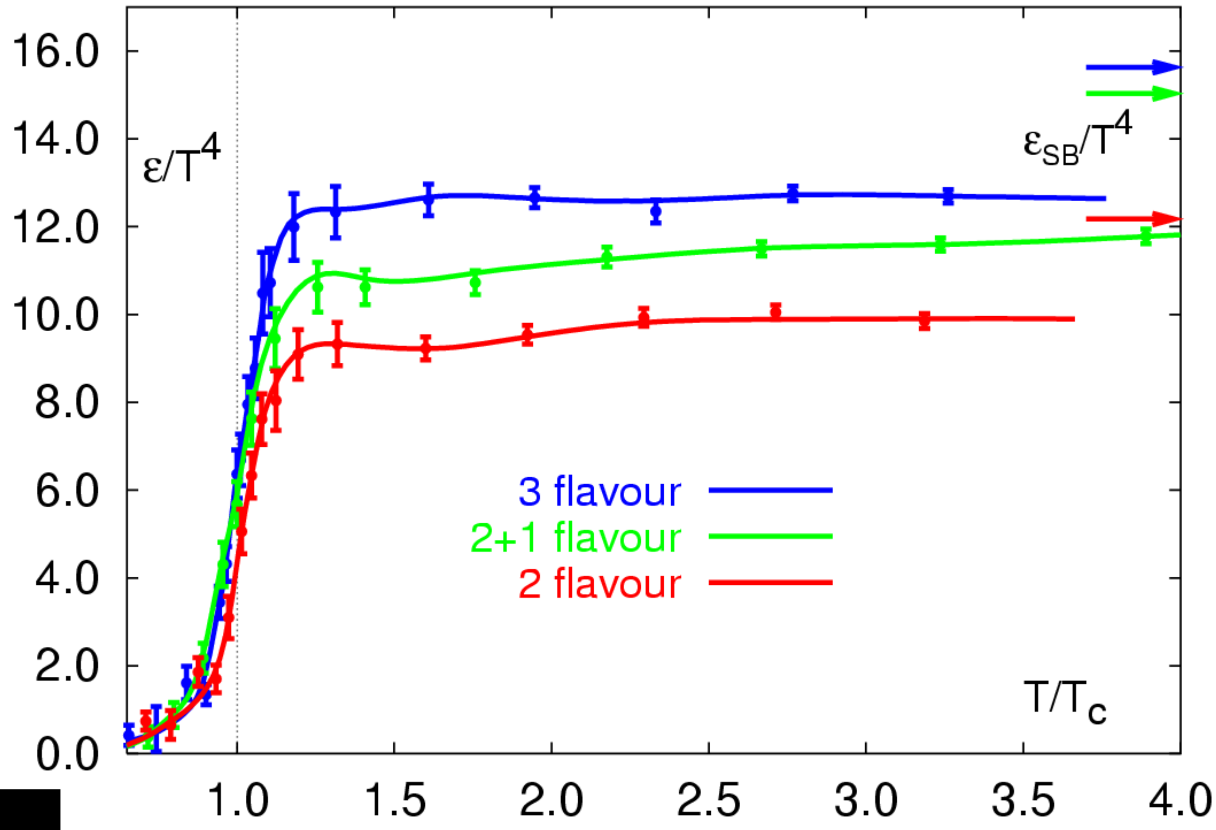
What is T_c ? - Lattice QCD

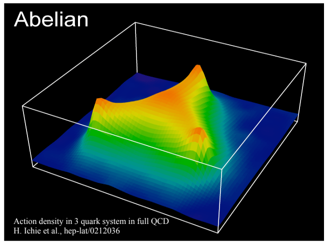


Action density in 3 quark system in full QCD
H. Ichie et al., hep-lat/0212036

What is T_c ? - Lattice QCD

- Coincident transitions: deconfinement and chiral symmetry restoration
- Recently extended to $\mu_B > 0$, order still unclear (1st, 2nd, crossover ?)

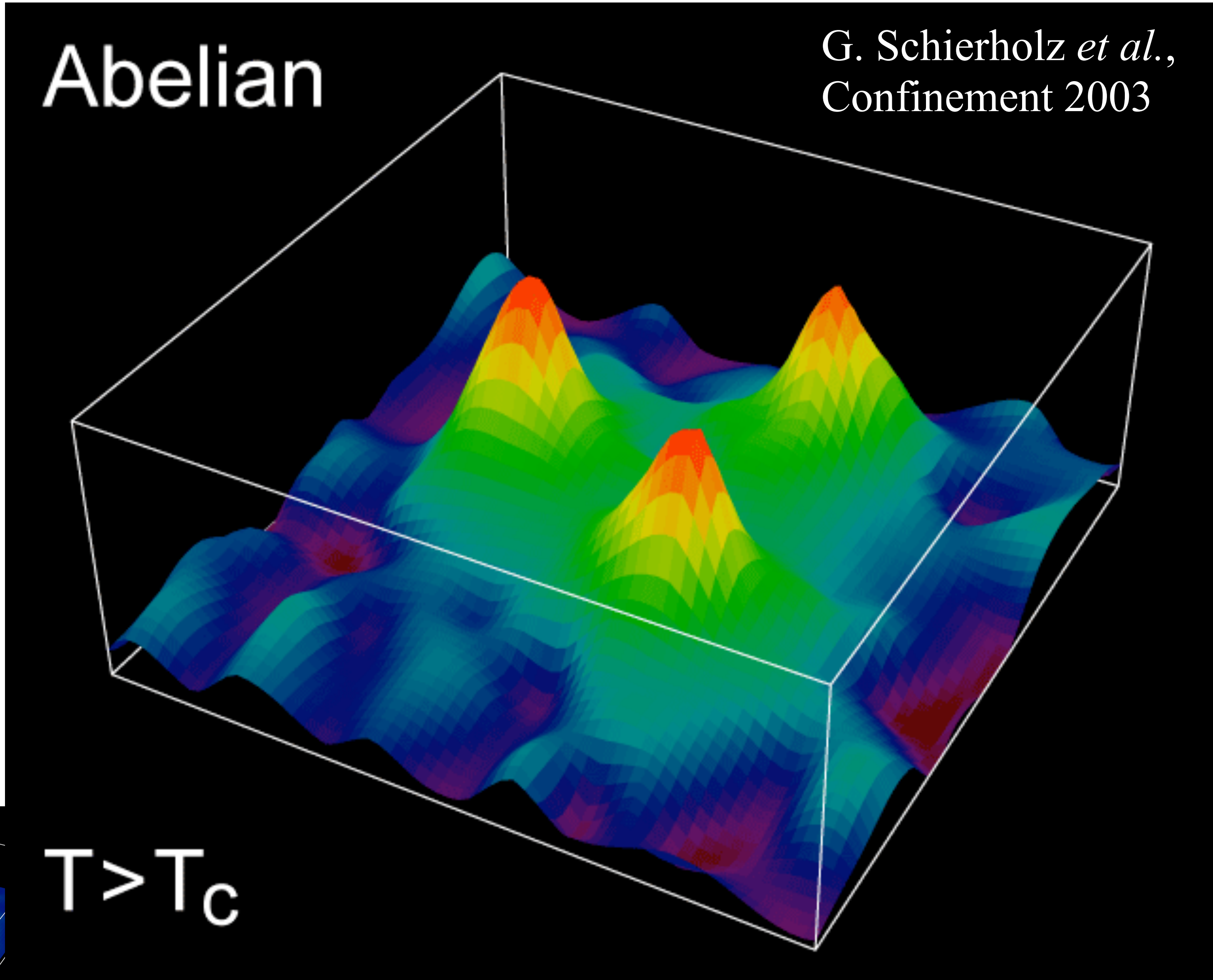


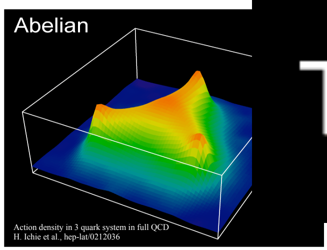


$T_C \approx 170$ MeV

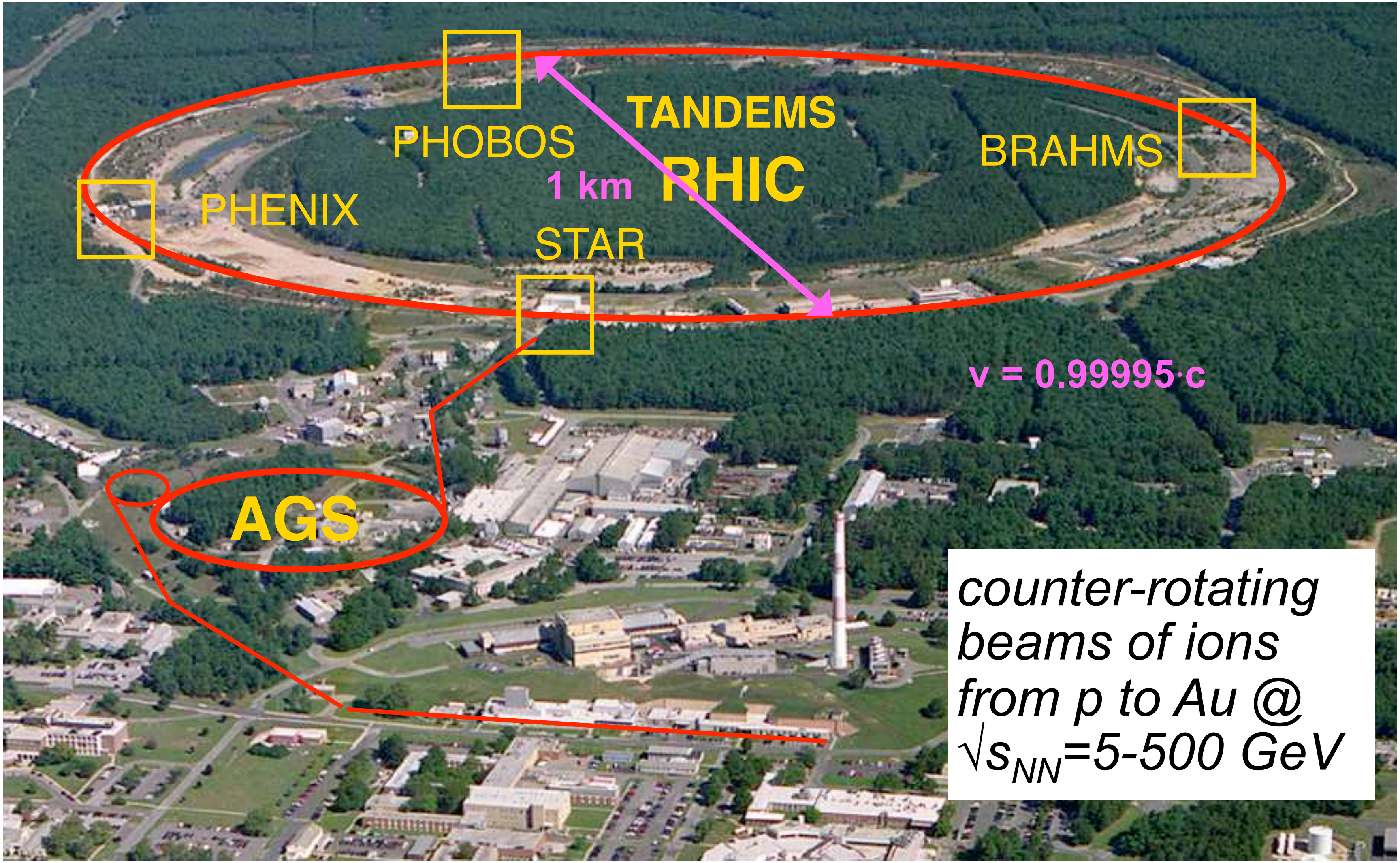
F. Karsch,
hep-ph/0103314

What is T_c ? - Lattice QCD





RHIC - a collider



counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

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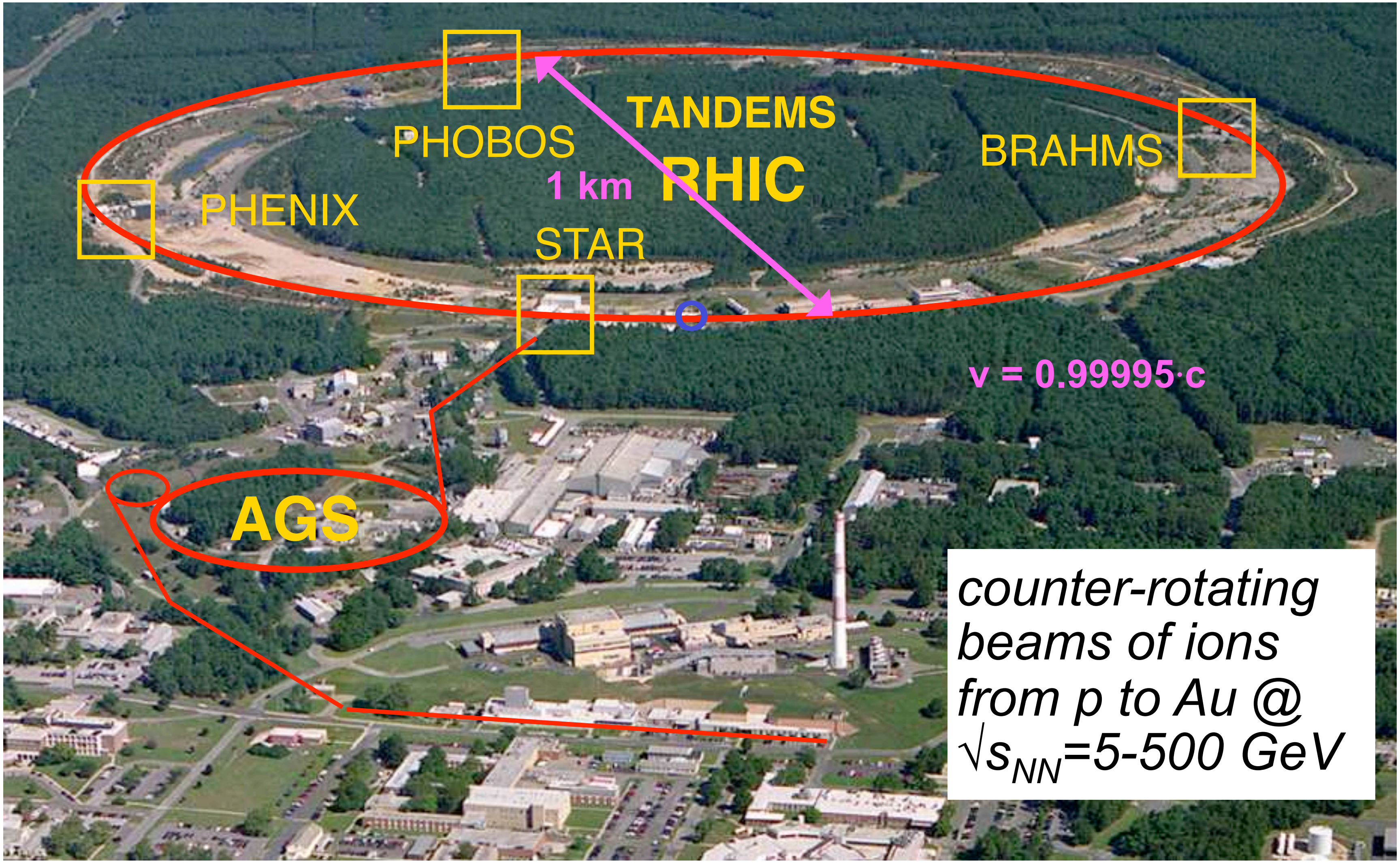
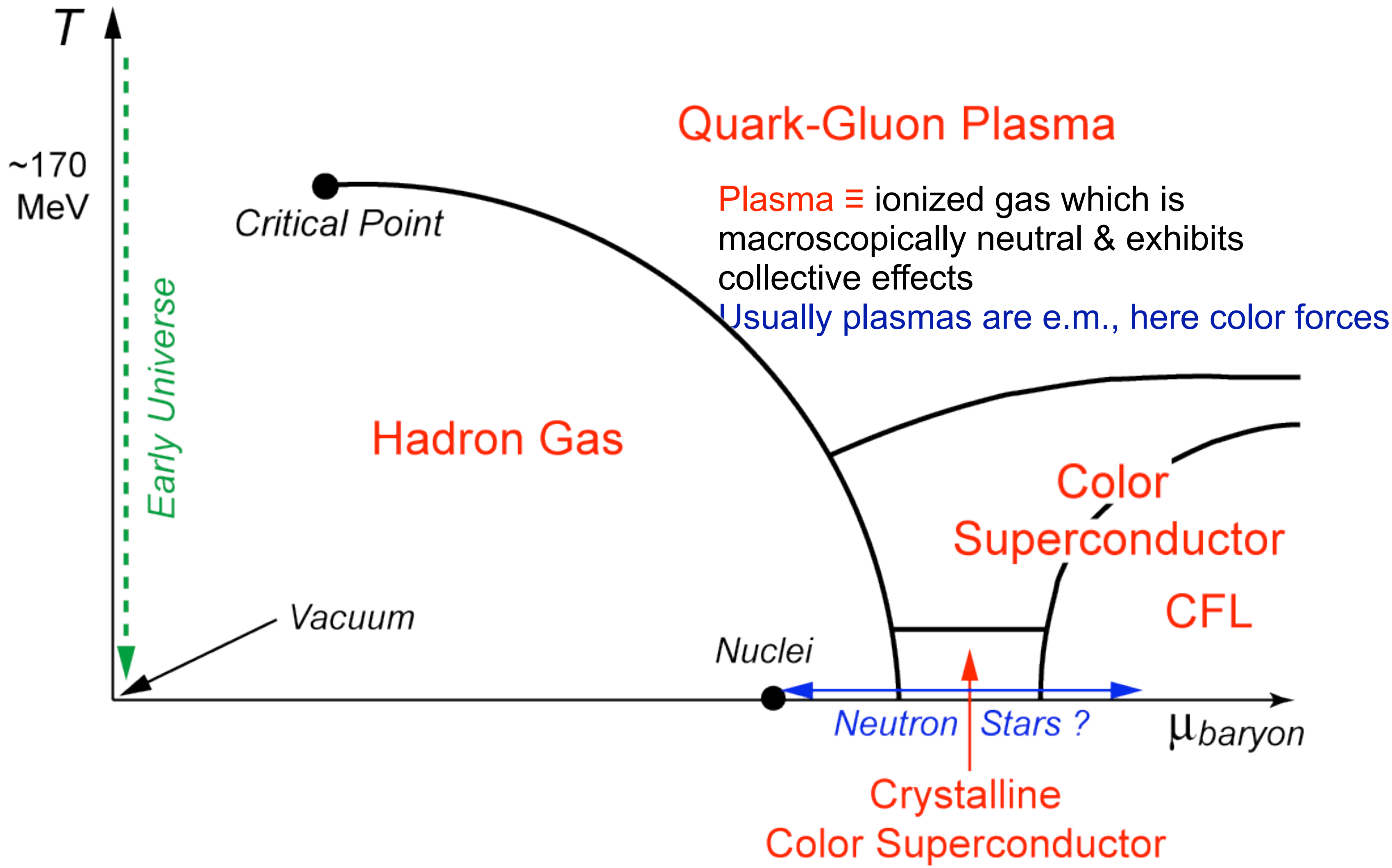


counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

RHIC and the LHC

	RHIC	LHC
Start date	2001	2009
Ion	Au-Au & p-p	Pb-Pb & p-p
Max $\sqrt{s}$	200 GeV	5.5 TeV
Circumference	2.4 miles	17 miles
Depth	On surface	175 m below ground
HI Exp.	BRAHMS,PHENIX, PHOBOS, STAR	ALICE, ATLAS, CMS
Located	BNL, New York, USA	CERN, Geneva, Switzerland

QCD phase diagram of hadronic matter



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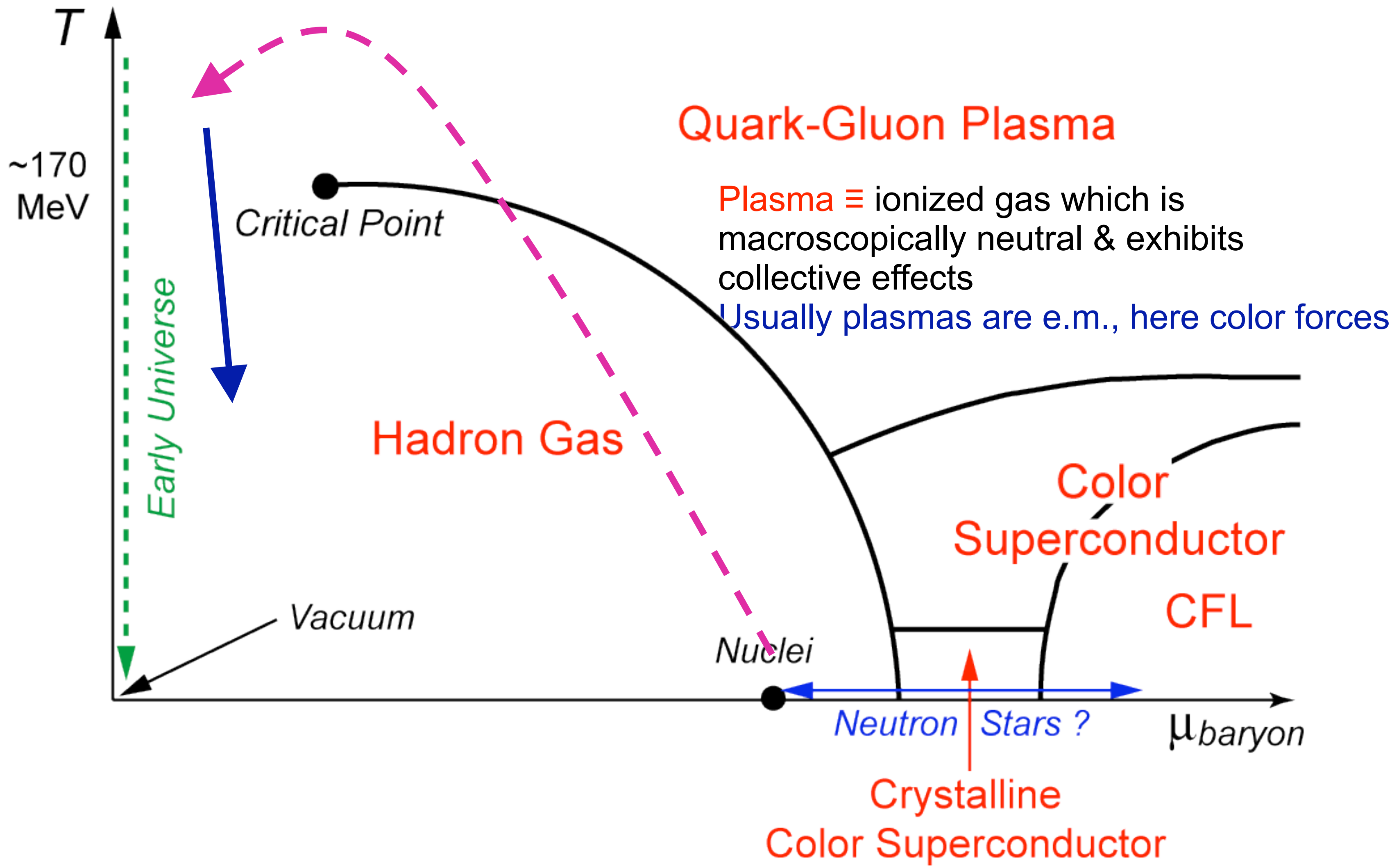
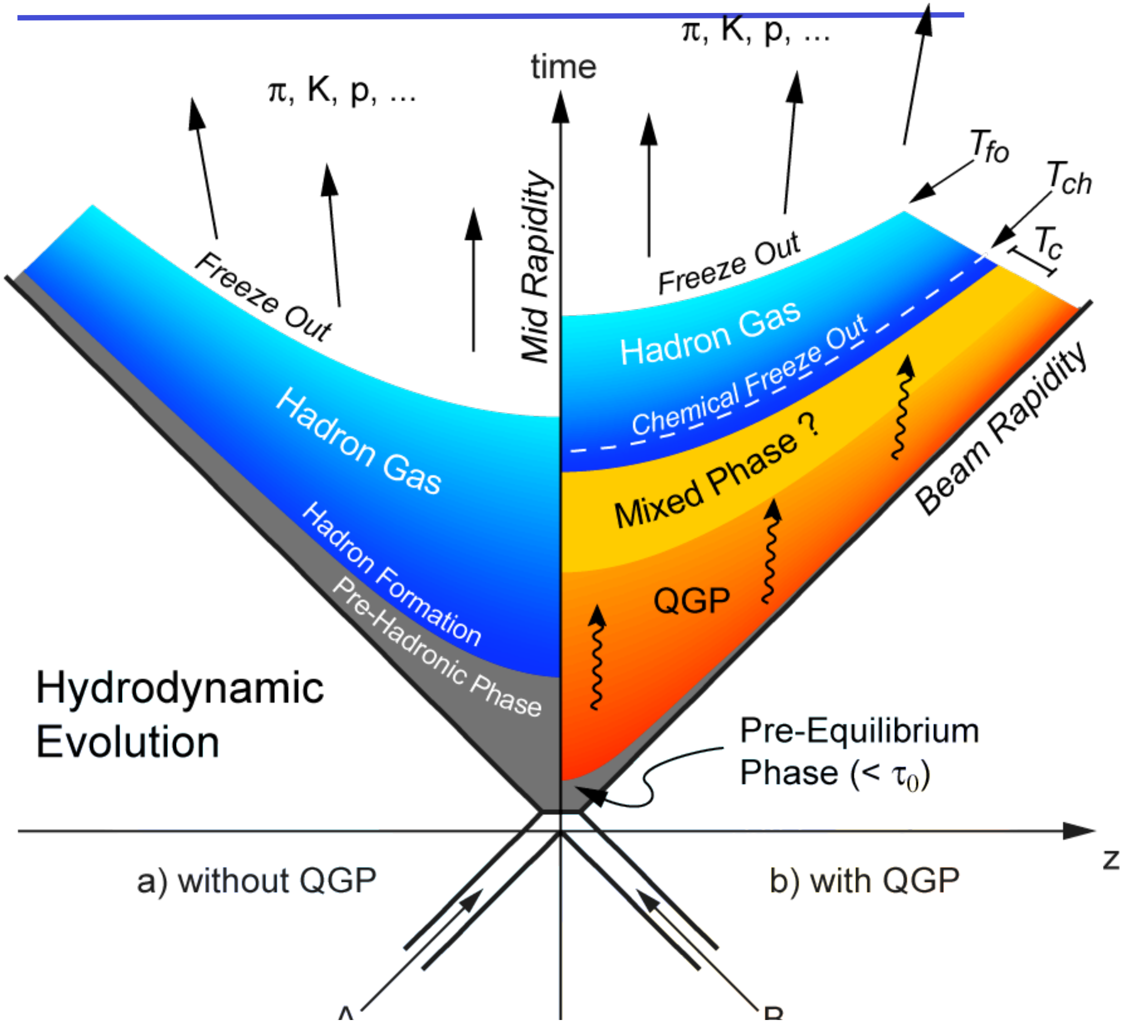


The phase transition in the laboratory



Chemical freeze-out ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

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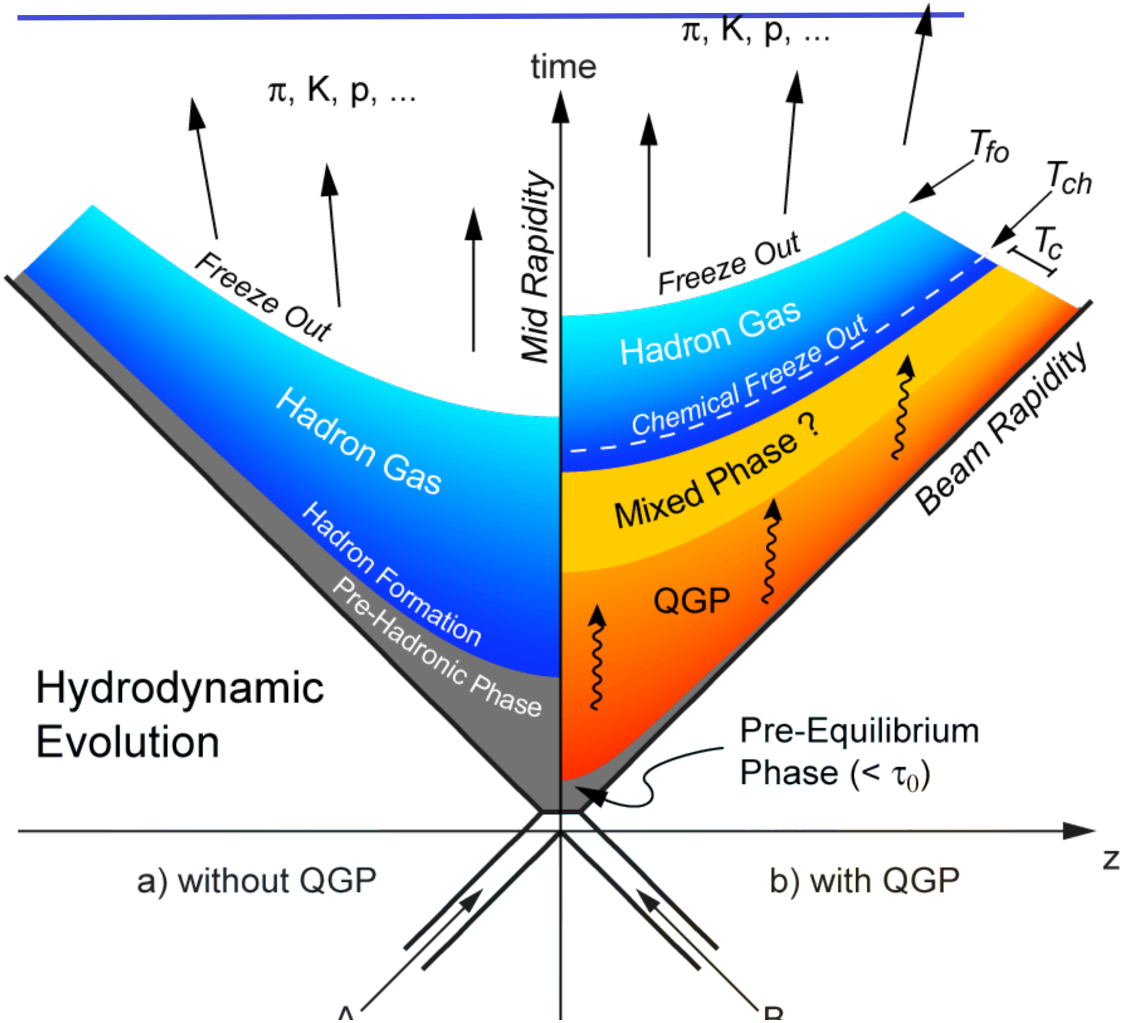

Lattice (2-flavor):
$T_C \approx 173\pm8$ MeV
$\varepsilon_C \approx (6\pm2)\ T^4 \approx 0.70$ GeV/fm^3

Remember: cold nuclear matter
$\varepsilon_{cold} \approx u\ /\ {}^4/_3\pi r_0^3 \approx 0.13$ GeV/fm^3

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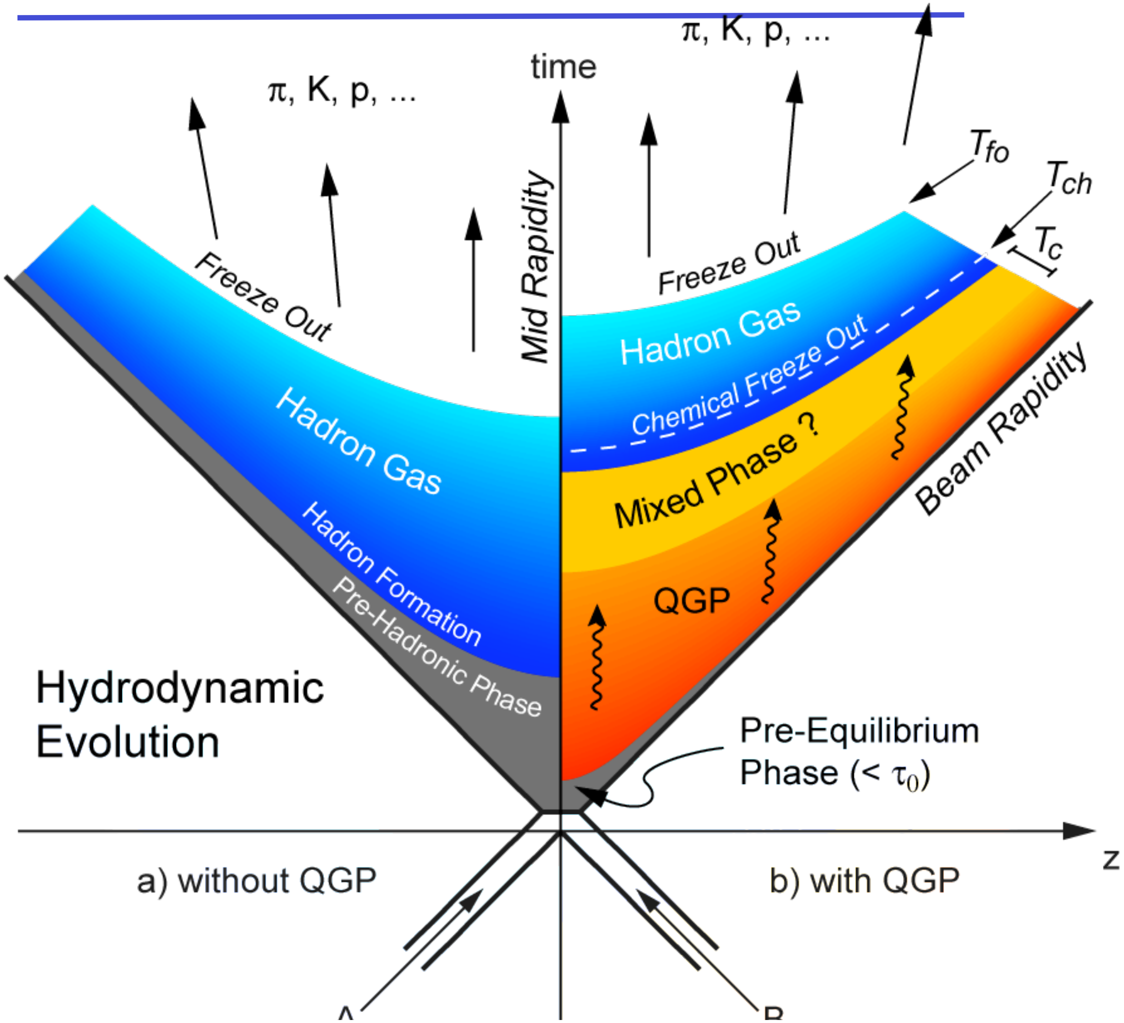

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Necessary but **not** sufficient condition

Tevatron (Fermilab)

$\varepsilon(\sqrt{s} = 1.8\text{TeV}\ \bar{p}p) >>$

$\varepsilon(\sqrt{s} = 200\text{GeV Au+Au RHIC})$

Thermal Equilibrium ⇒

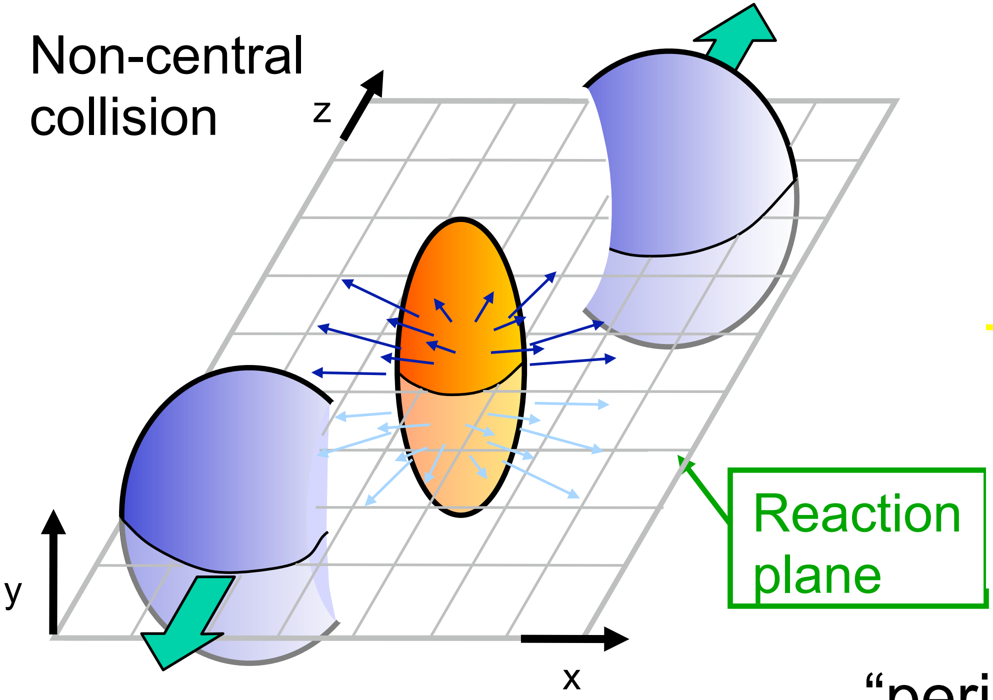
many constitutents

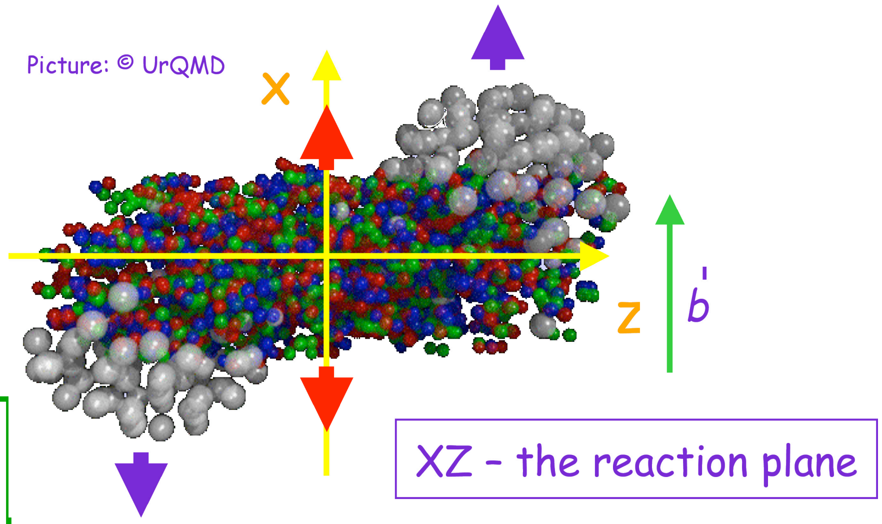
Chemical freeze-out ($T_{ch} \leq T_c$): inelastic scattering ceases

Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

Size matters !!!

Geometry of a heavy-ion collision





"<u>peripheral</u>" collision ($b \sim b_{max}$)

"<u>central</u>" collision ($b \sim 0$)

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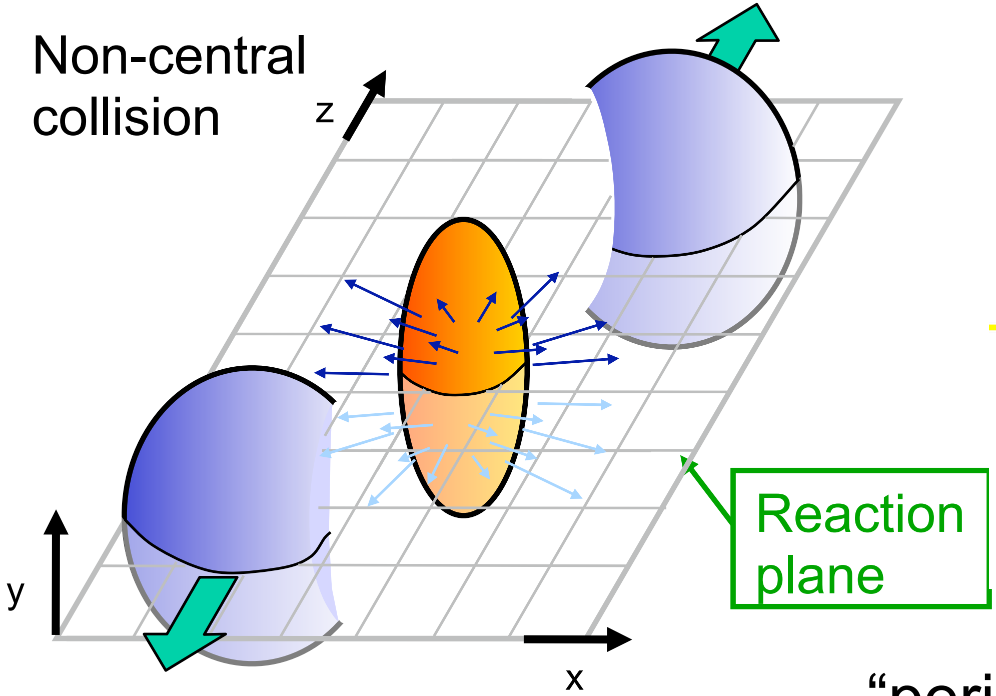

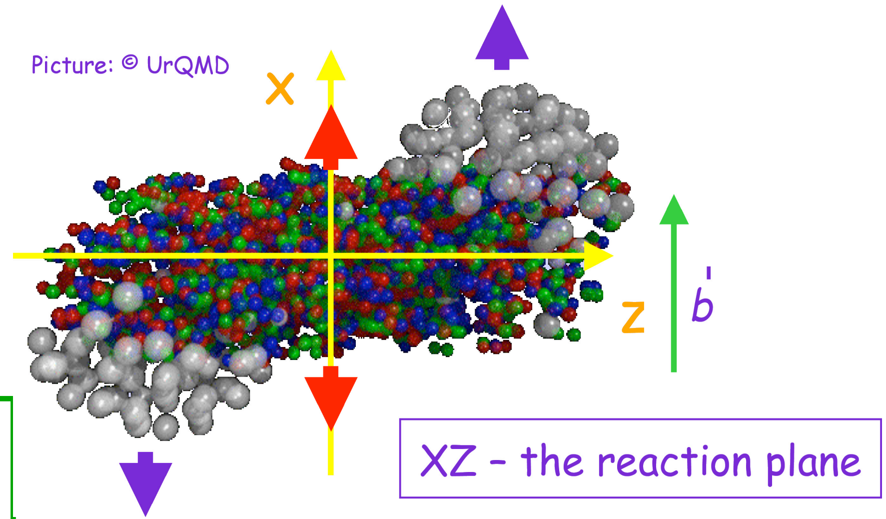

"<u>peripheral</u>" collision ($b \sim b_{max}$)

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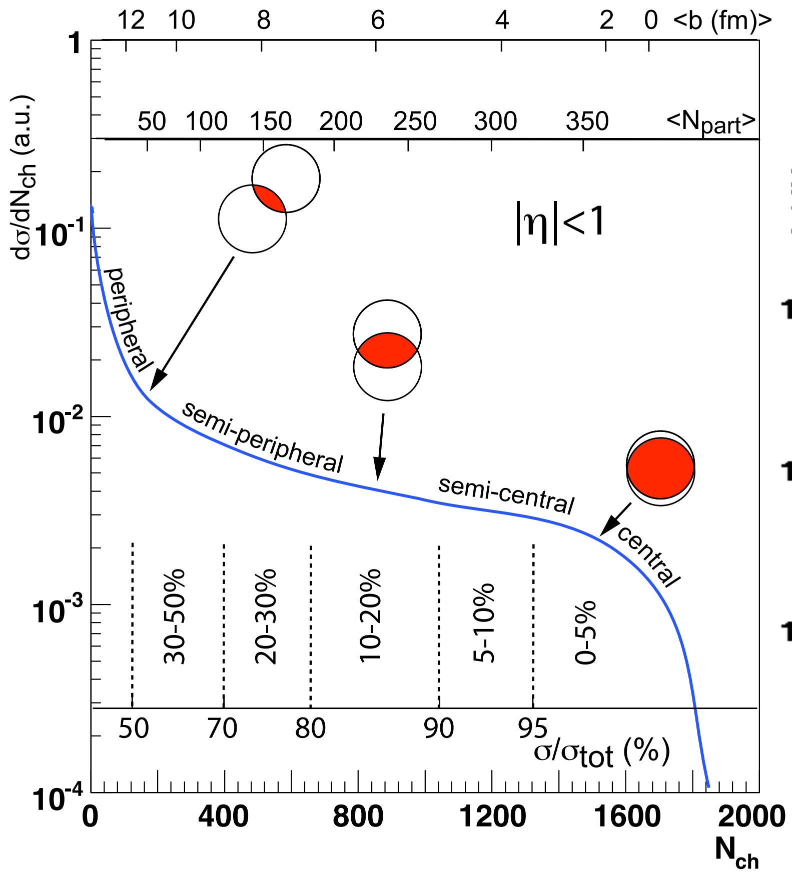
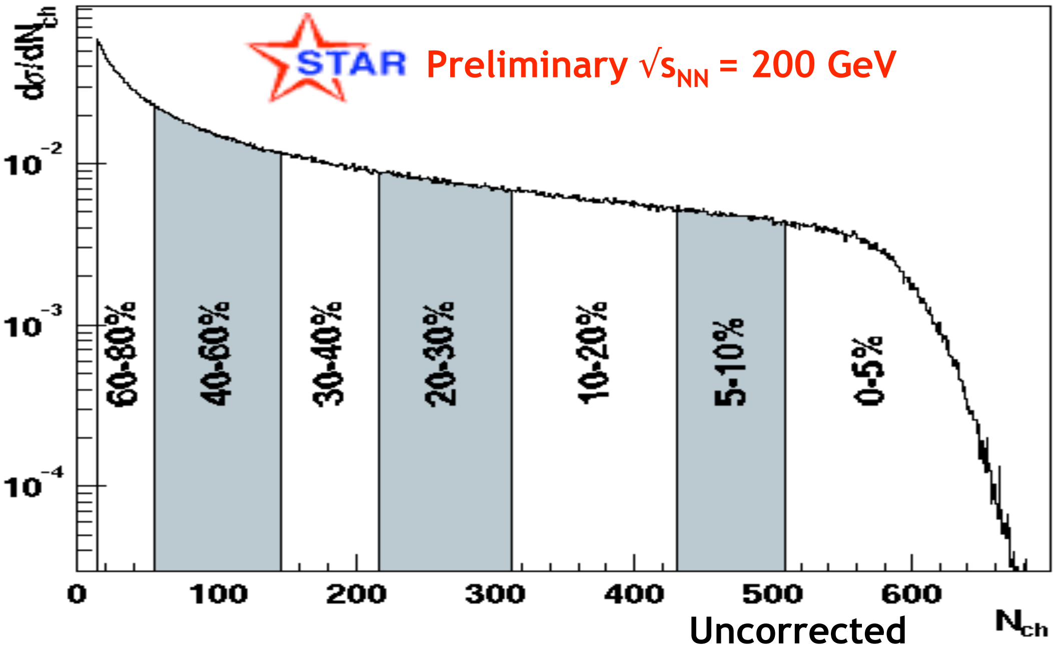
Number of participants (N_{part}): number of incoming nucleons (participants) in the overlap region

Number of binary collisions (N_{bin}): number of equivalent inelastic nucleon-nucleon collisions

$N_{bin} \geq N_{part}/2$

Comparing to data heavy-ion collision

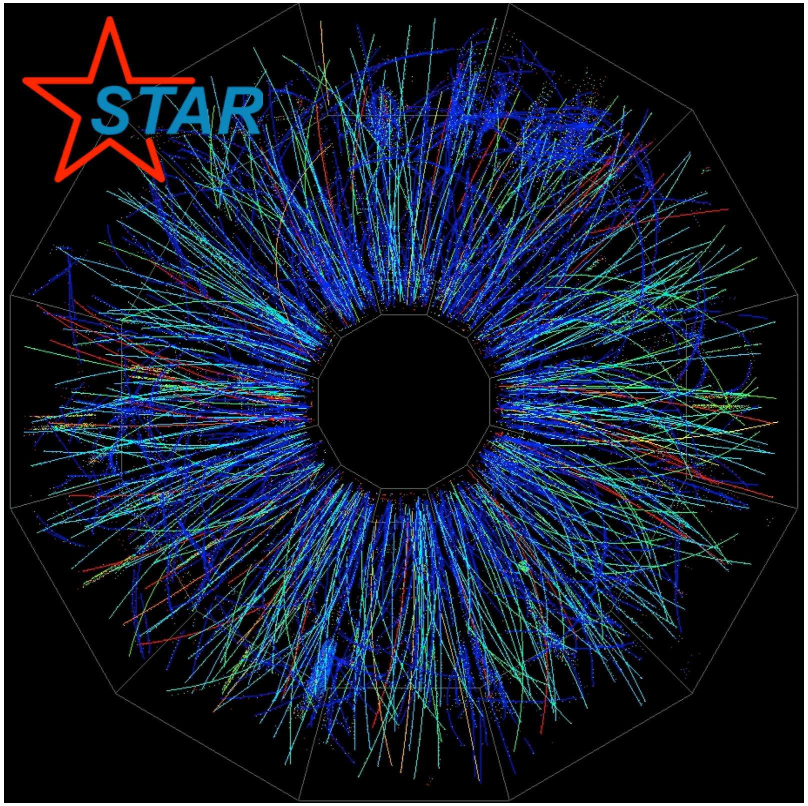




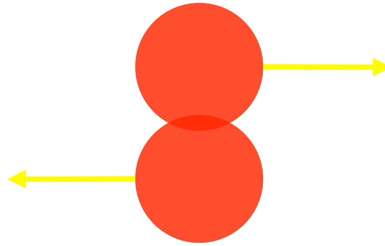
Good agreement between data and calculation

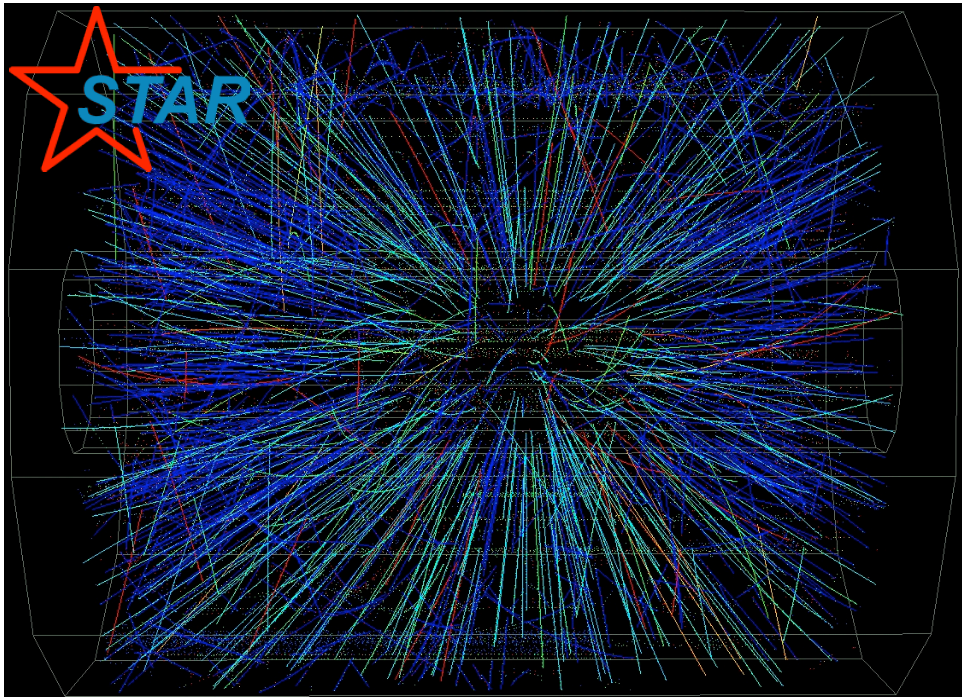
Measured mid-rapidity particle yield can be related to size of overlap region

A peripheral Au-Au collision



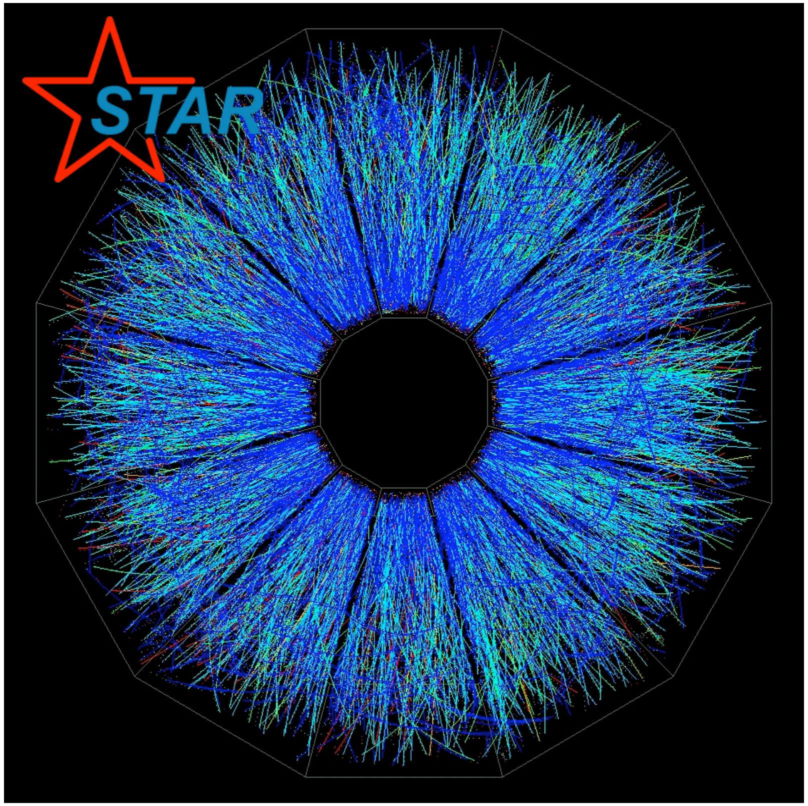
Peripheral Collision





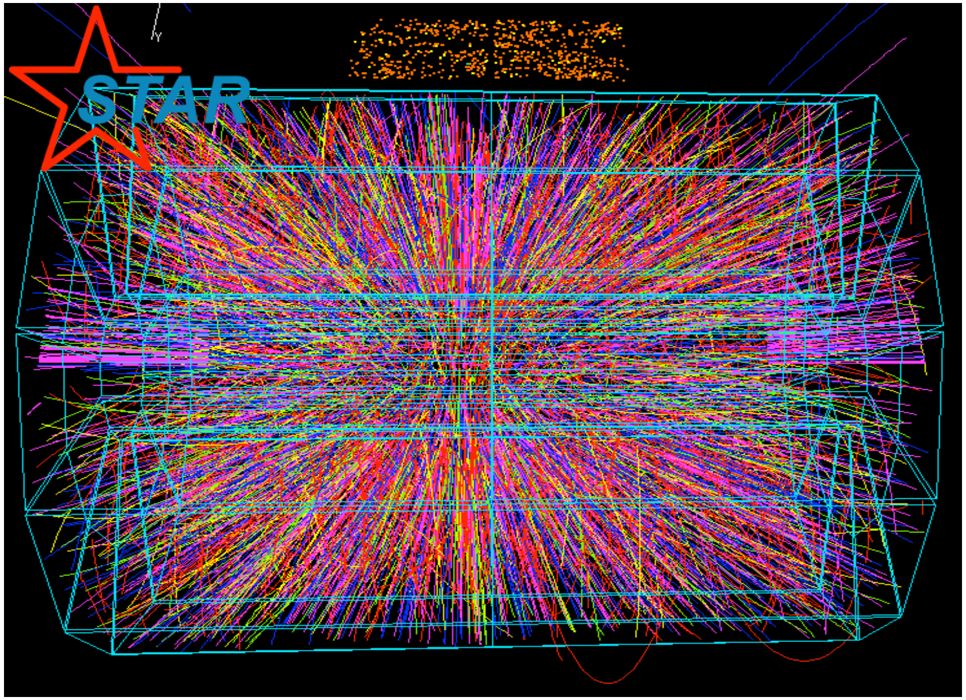
Color ⇒ Energy loss in TPC gas

39.4 TeV in central Au-Au collision



- Only charged particles shown

- Neutrals don't ionise the TPC's gas so are not "seen" by this detector.



>5000 hadrons and leptons

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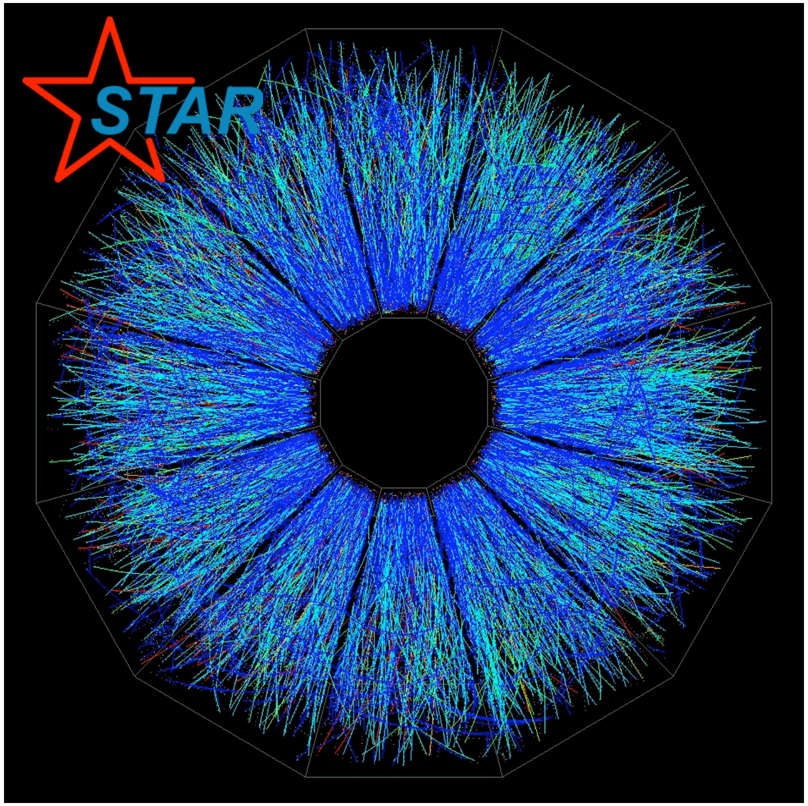

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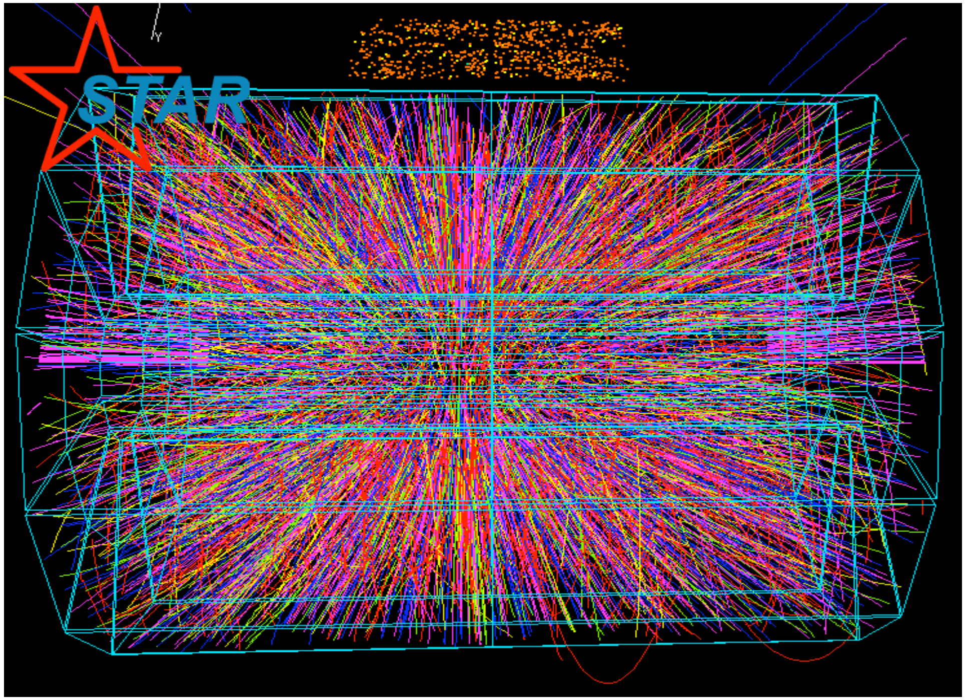

>5000 hadrons and leptons

<u>26 TeV</u> is removed from colliding beams.

The energy is contained in one collision

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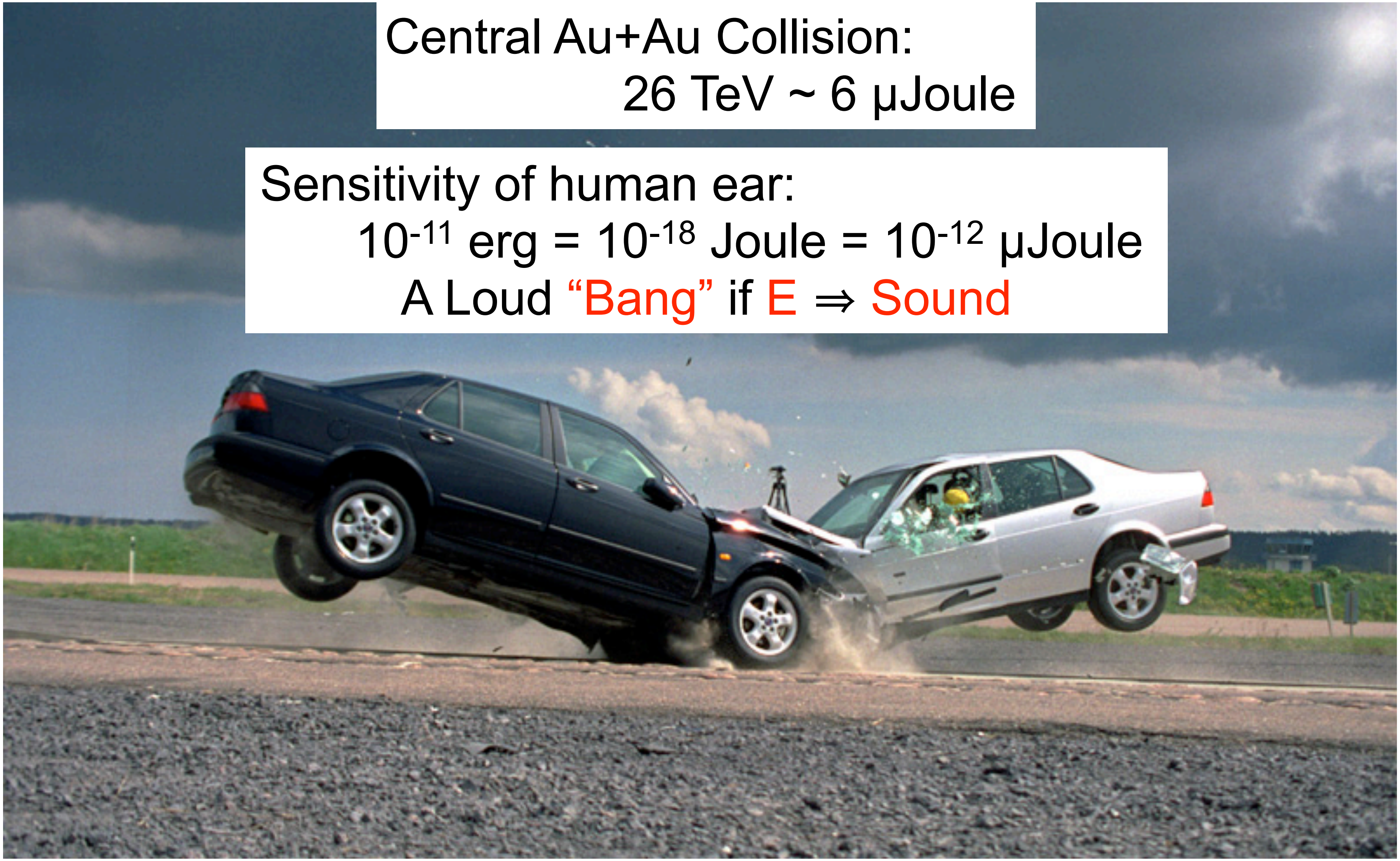

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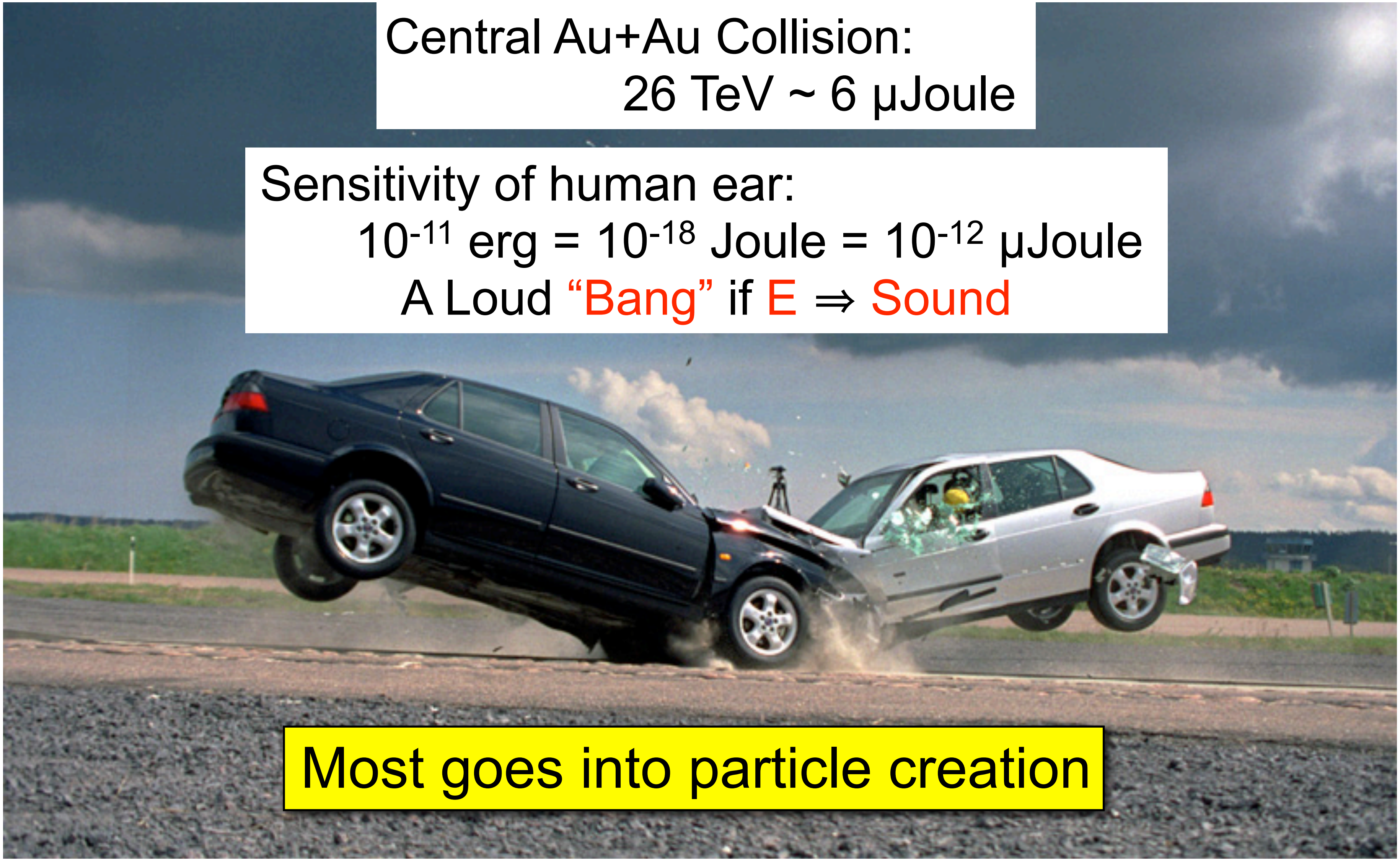
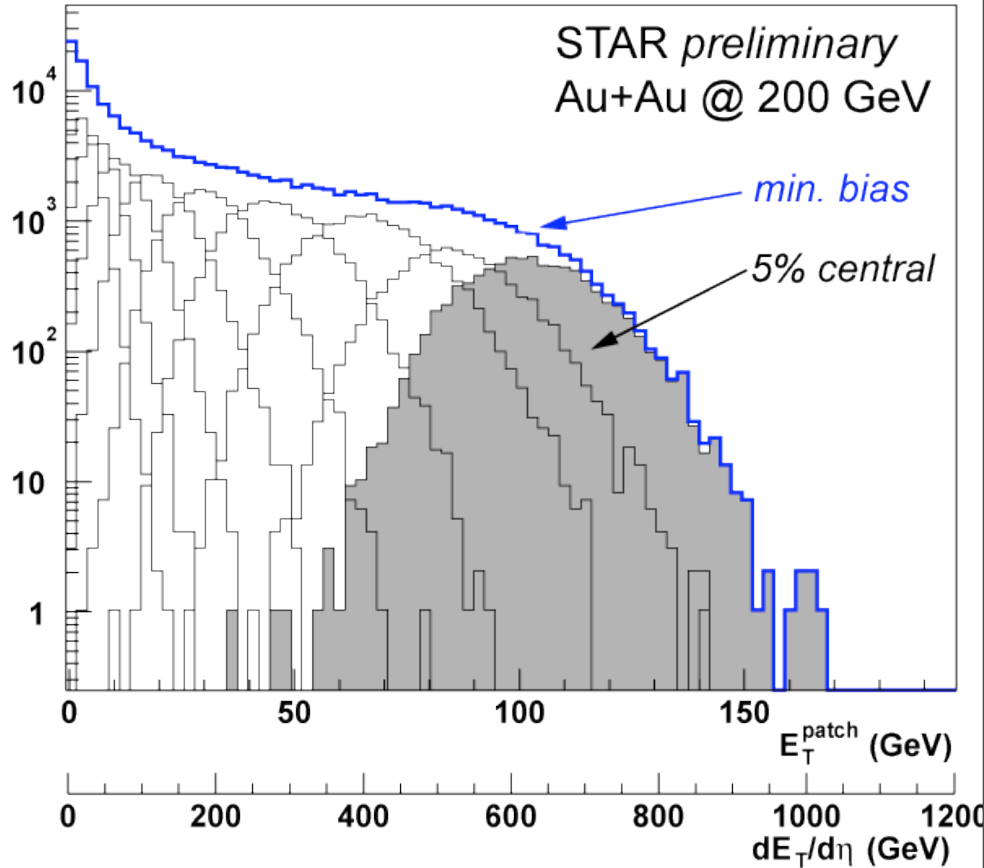


Energy density in central Au-Au collisions

- use calorimeters to measure total energy



Energy density in central Au-Au collisions

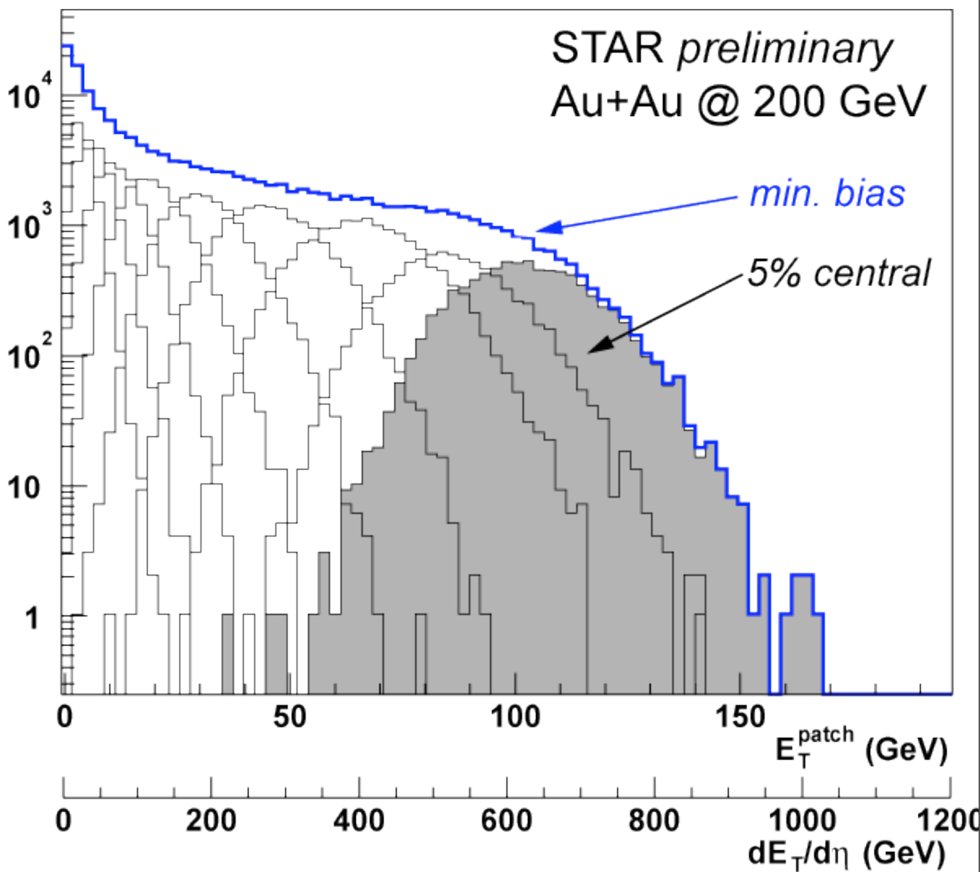
- use calorimeters to measure total energy
- estimate volume of collision

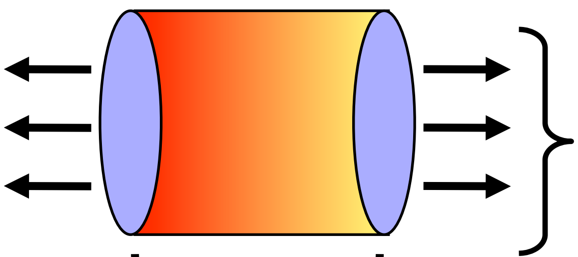
Bjorken-Formula for Energy Density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system ($t_0 \sim$ 1 fm/c)





πR^2

$$dz = \tau_0 dy$$

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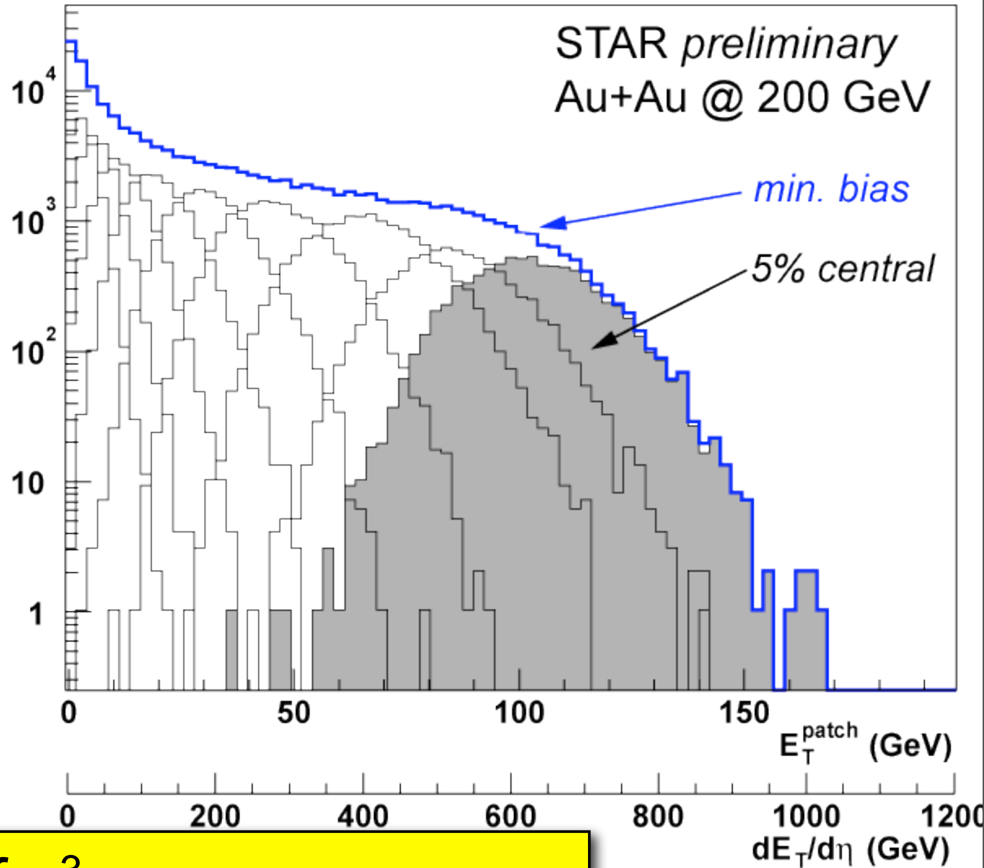

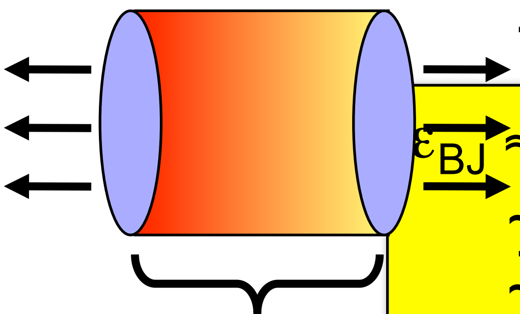

$$dz = \tau_0 dy$$

$\varepsilon_{BJ} \approx 5.0$ GeV/fm^3 πR^2

~30 times normal nuclear density

~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

5 GeV/fm^3. Is that a lot?

In a year, the U.S. uses ~100 quadrillion BTUs of energy (1 BTU = 1 burnt match):

$$100 \times 10^{15} BTU \times \frac{1060 J}{BTU} \times \frac{1 eV}{1.6 \times 10^{-19} J} = 6.6 \times 10^{38} eV$$

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At 5 GeV/fm^3, this would fit in a volume of:

$$6.6 \times 10^{38} eV \div \frac{5 \times 10^{9} eV}{fm^3} = 1.3 \times 10^{29} fm^3$$

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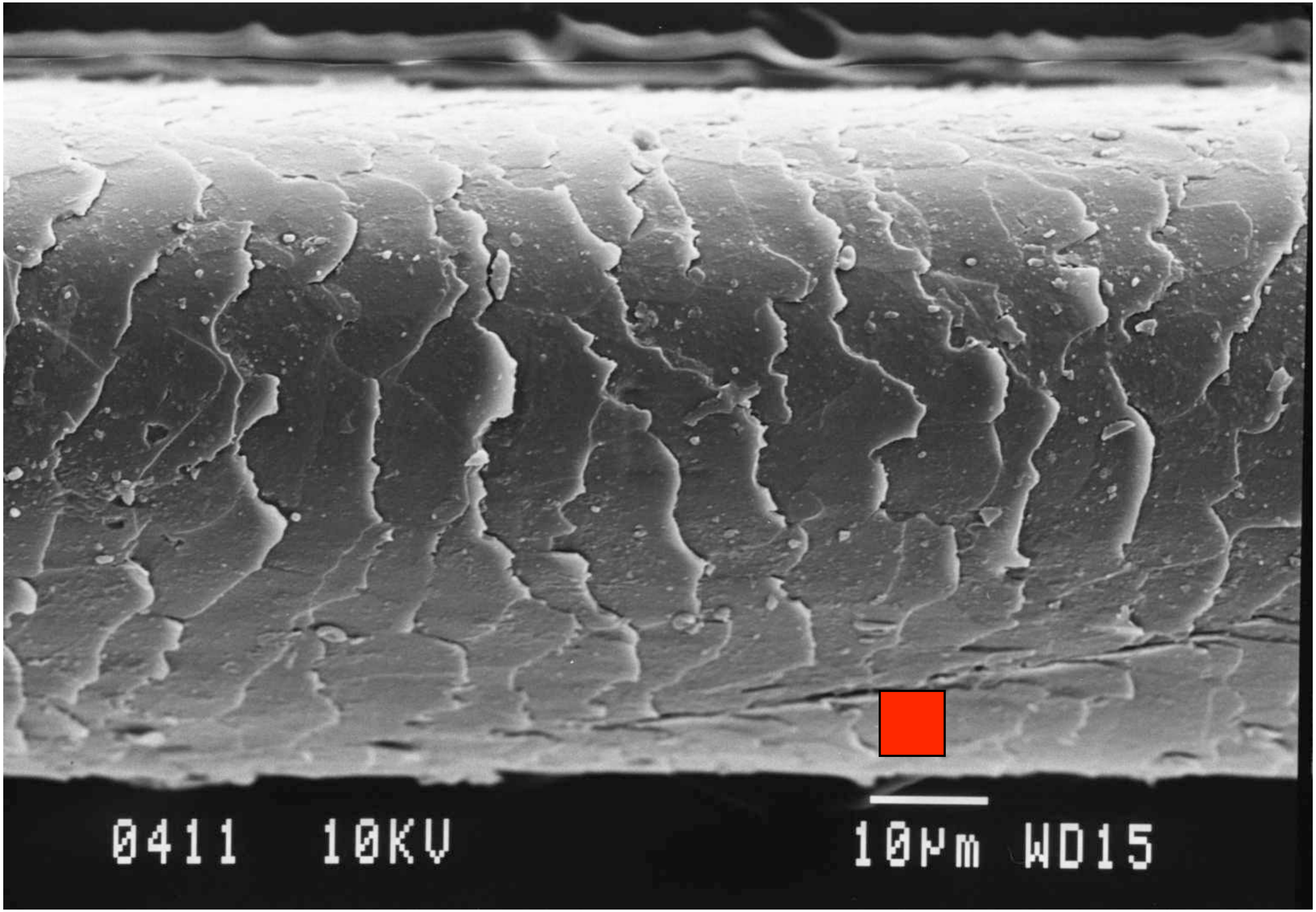
Or, in other words, in a box of the following dimensions:

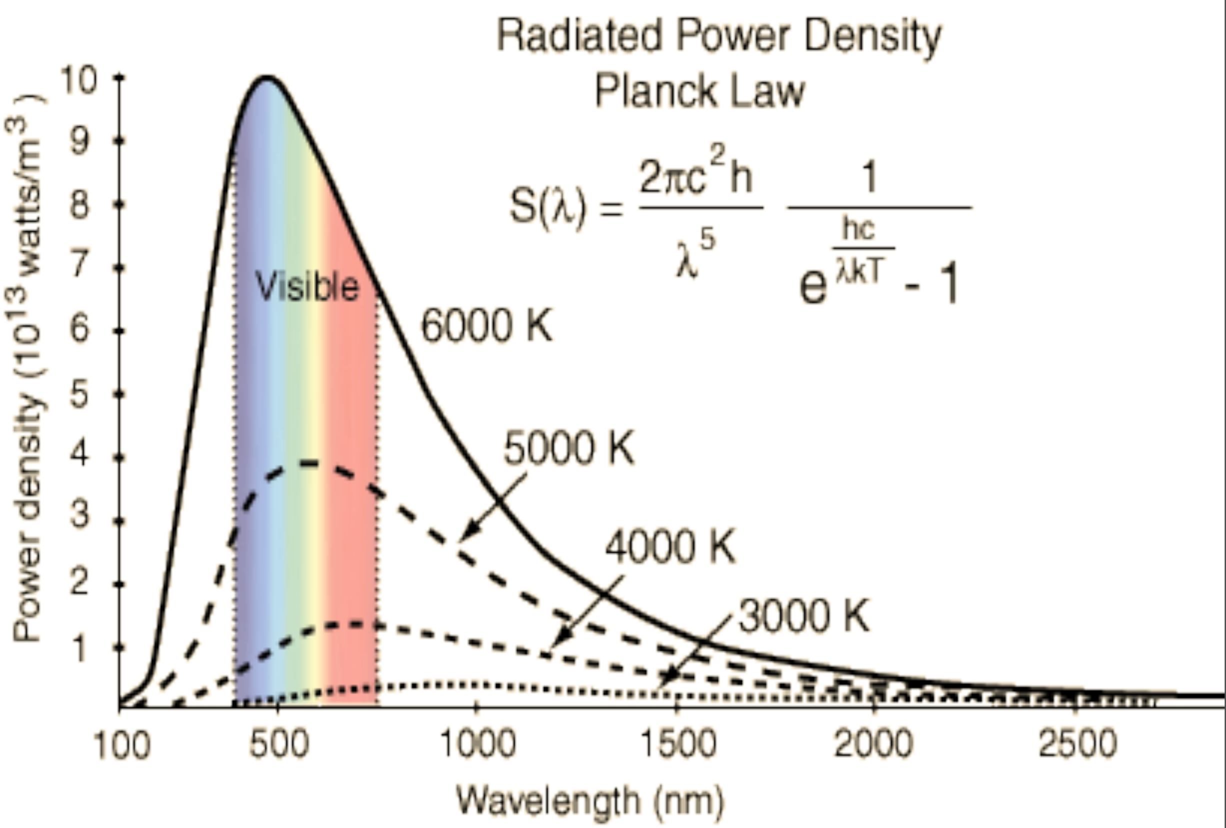
$$\boxed{\sqrt[3]{1.3 \times 10^{29}\ fm^3} = 5 \times 10^{9}\ fm = 5 \mu m}$$

A human hair



Measuring the initial temperature

Planck distribution describes intensity as a function of the wavelength of the emitted radiation



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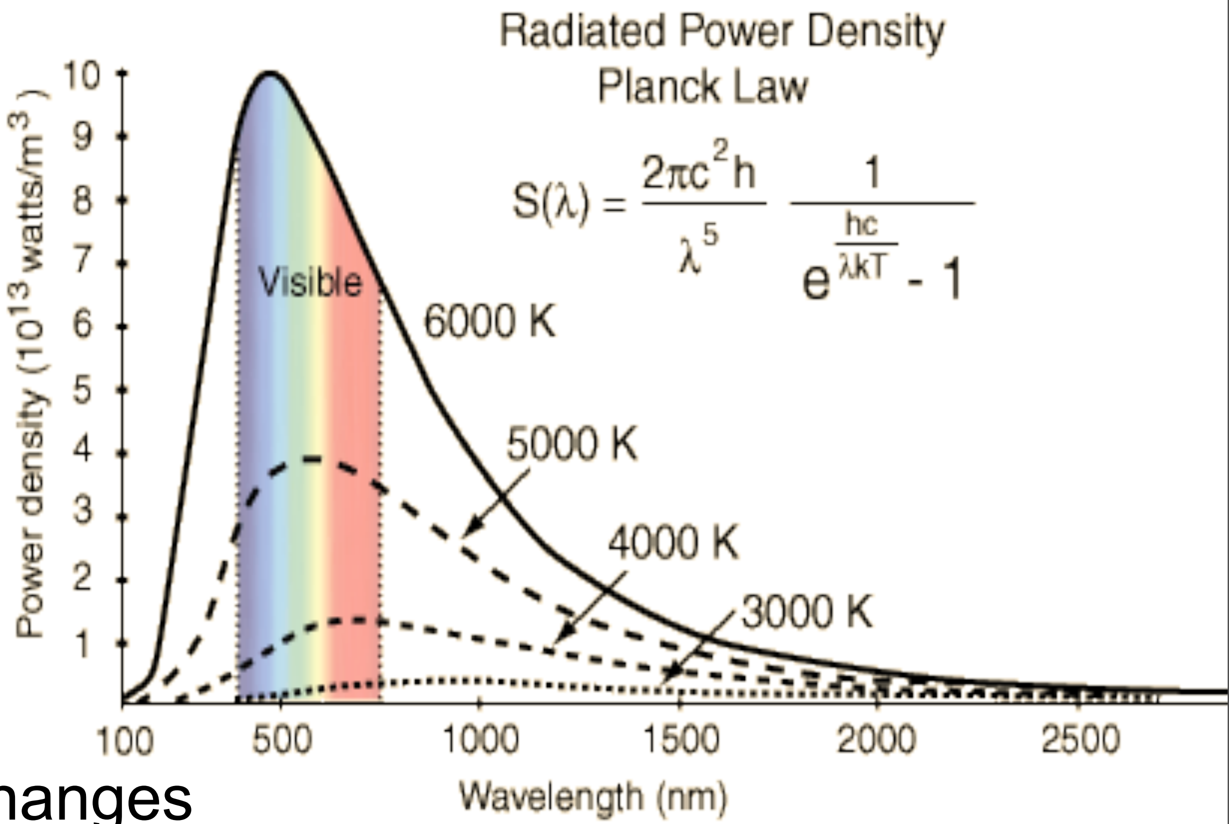
"Blackbody" radiation is the spectrum of radiation emitted by an object at temperature T



As T increases curve changes

Photons have no charge or color → don't interact with medium

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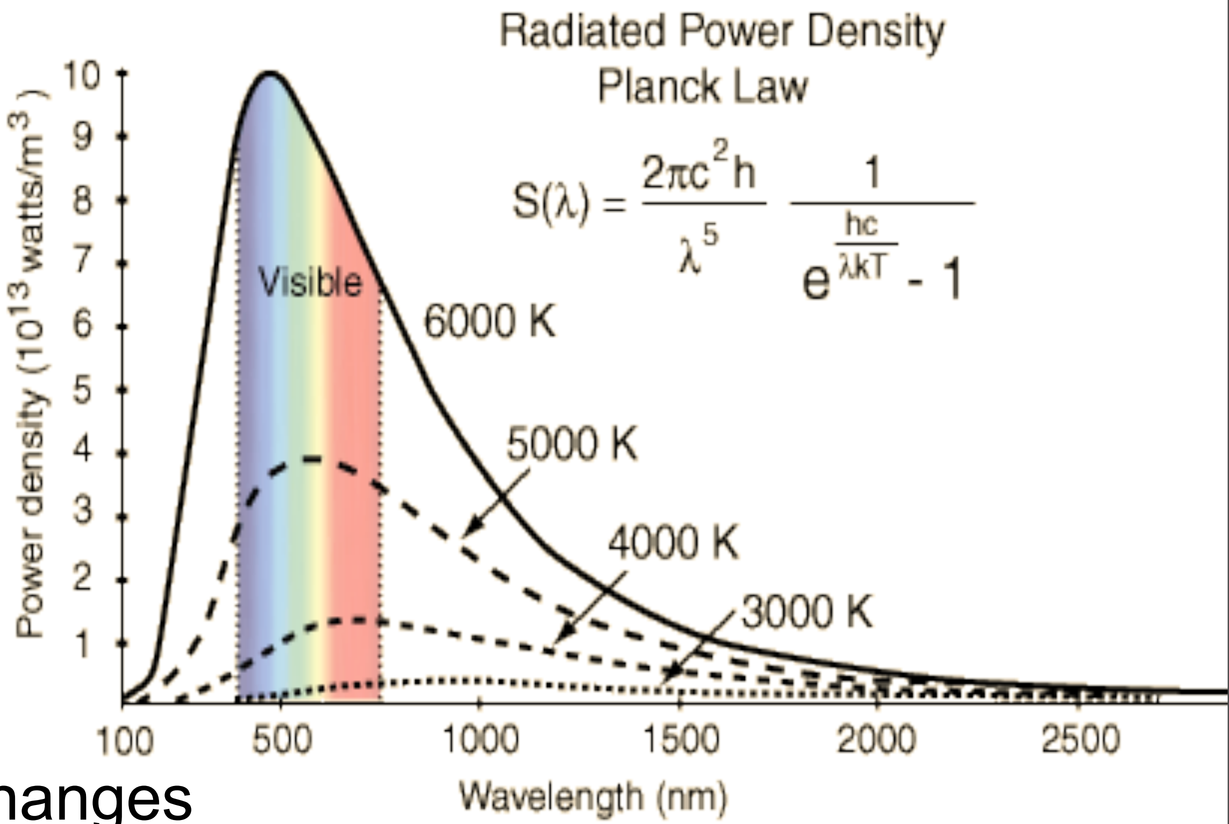


Photons have no charge or color → don't interact with medium

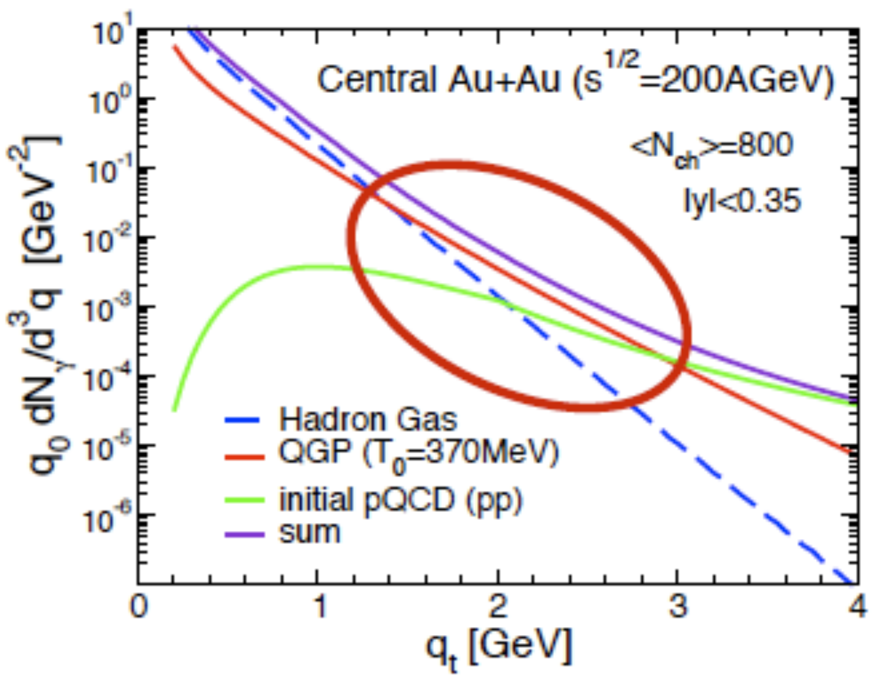
$\boxed{\gamma \text{ reveals early temperature of QGP}}$

Measuring the initial temperature

γ emitted over all lifetime → convolution of all temperatures

Theory now well developed

Corrections under control



QGP dominates
$1 < p_T < 3$ GeV/c

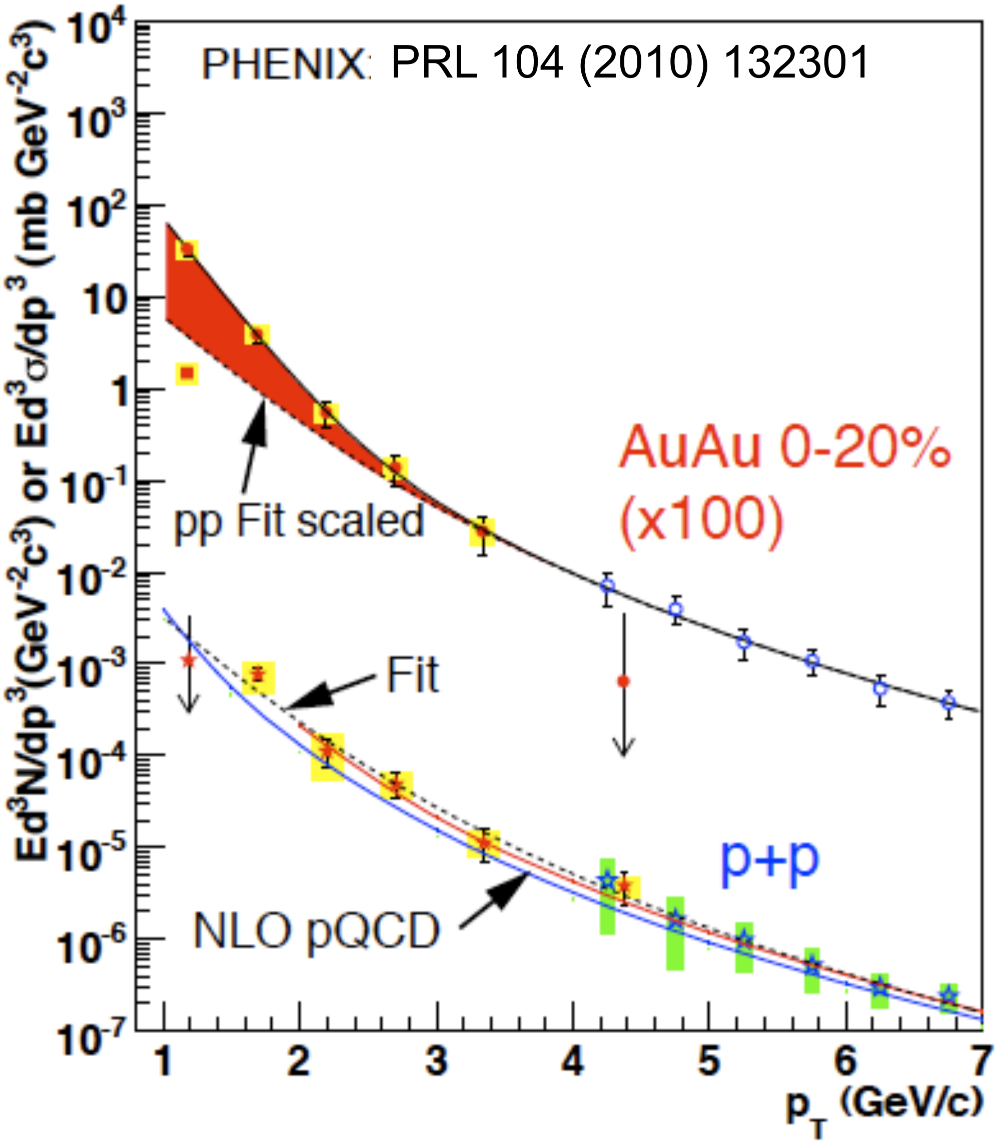
Experimentally photons a complete pain!

Calorimetry
- granularity and resolution

Large background
- $\pi^0/\eta \rightarrow \gamma\gamma$
- Losses from conversions
- Hadronic contamination

Signal:Background ~1:10

Measuring the initial temperature



After background subtraction:

Emission rate and shape consistent with that from a hot thermally equilibrated medium

T = 300 - 600 MeV
τ = 0.15-0.6 fm/c

Large uncertainty due to correlated pair background i.e. jets

What is the temperature of the medium?

- Statistical Thermal Models:
  - Assume a system that is thermally (constant T_{ch}) and chemically (constant n_i) equilibrated
  - System composed of non-interacting hadrons and resonances
  - Obey conservation laws: Baryon Number, Strangeness, Isospin

- Given T_{ch} and μ 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

Fitting the particle ratios

Number of particles of a given species related to temperature

$$dn_i \sim e^{-(E-\mu_B)/T} d^3p$$

- Assume all particles described by same temperature T and μ_B
- one ratio (e.g., $\bar{p}$ / p) determines μ / T :

$$\frac{\bar{p}}{p} = \frac{e^{-(E+\mu_B)/T}}{e^{-(E-\mu_B)/T}} = e^{-2\mu_B/T}$$

- A second ratio (e.g., K / π) provides T → μ

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K-E\pi)/T}$$

- Then all other hadronic ratios (and yields) defined

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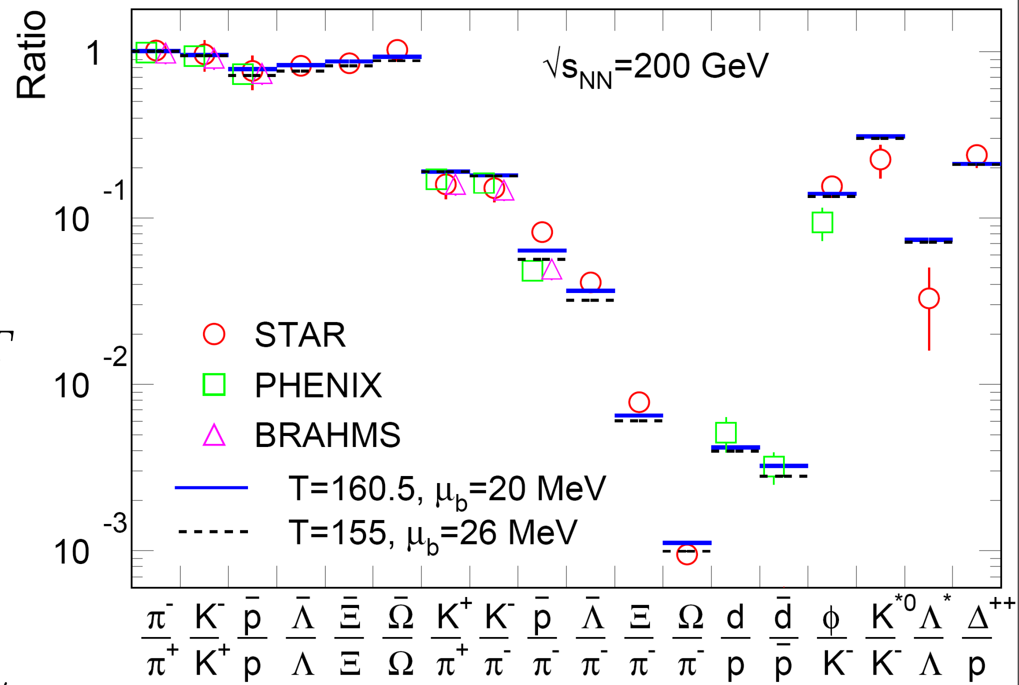
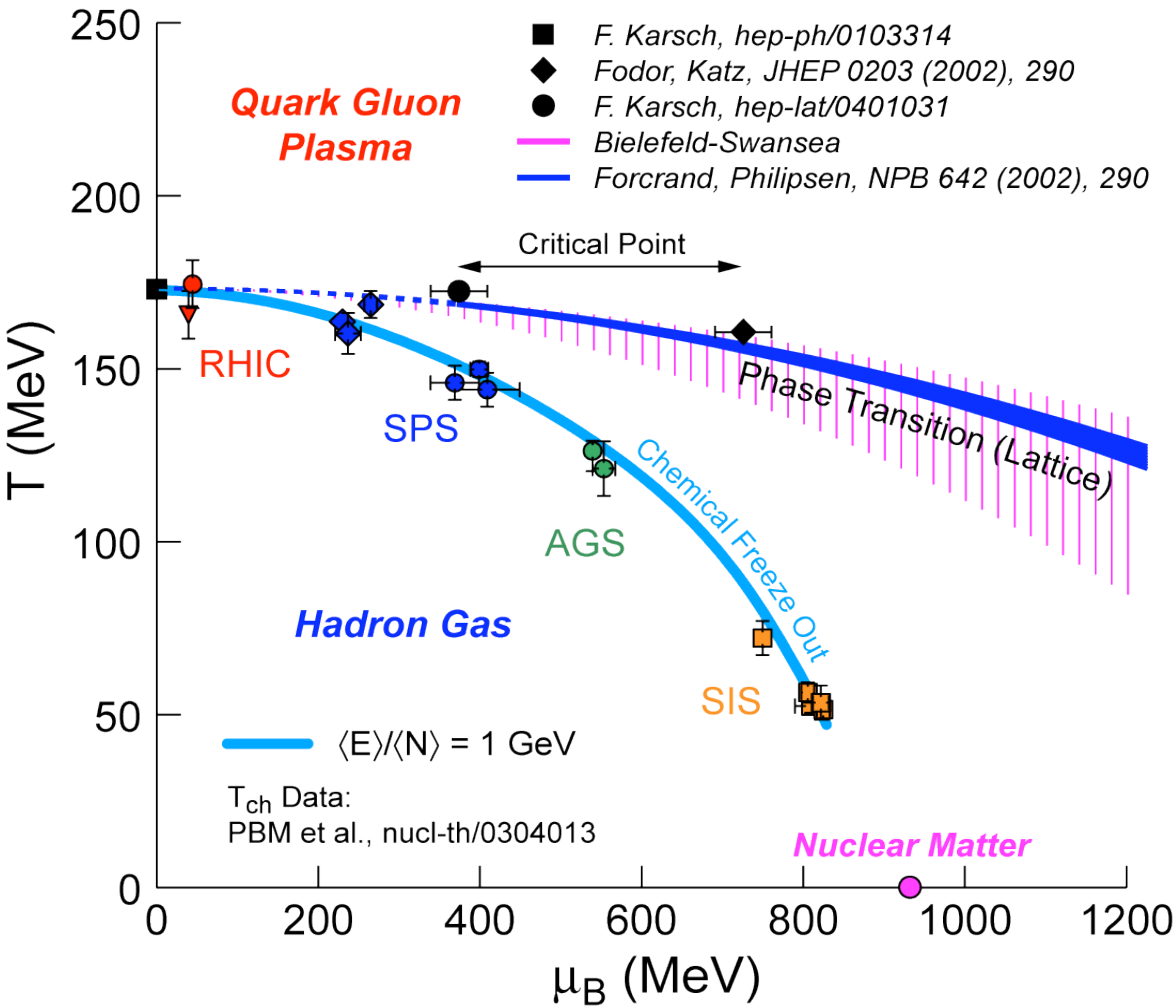
A. Adronic *et al.*, NPA772:167



T ~ 160 MeV, μ_b ~ 20 MeV

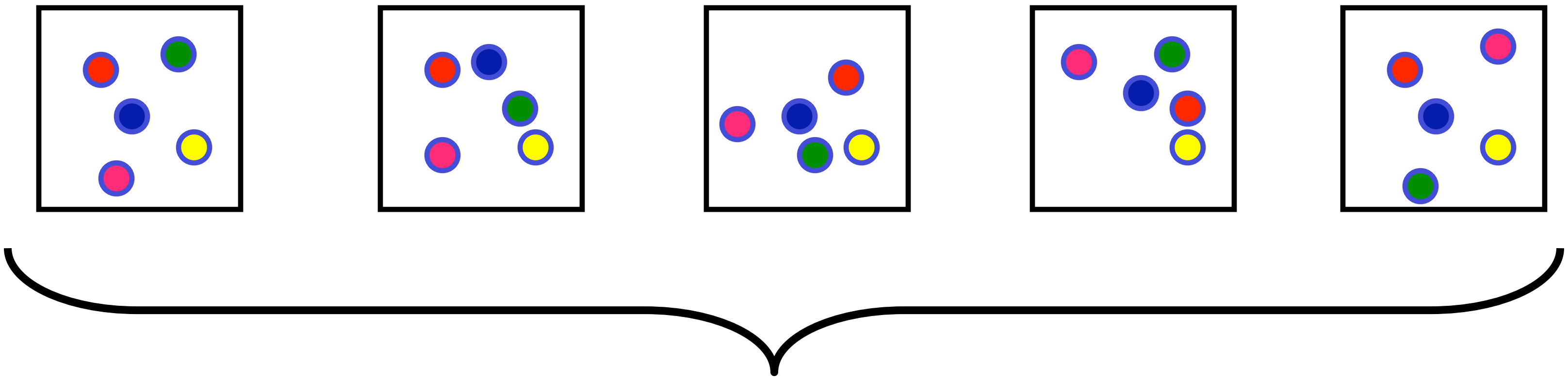
Initial Temperature probably much higher

Where RHIC sits on the phase diagram



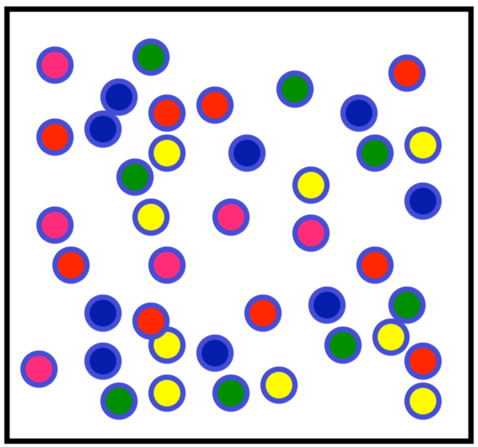
Statistics ≠ thermodynamics

p+p



Ensemble of events constitutes a statistical ensemble
T and μ are simply Lagrange multipliers
"Phase Space Dominance"

A+A



One (1) system is already statistical !

- We can talk about pressure
- T and μ are more than Lagrange multipliers

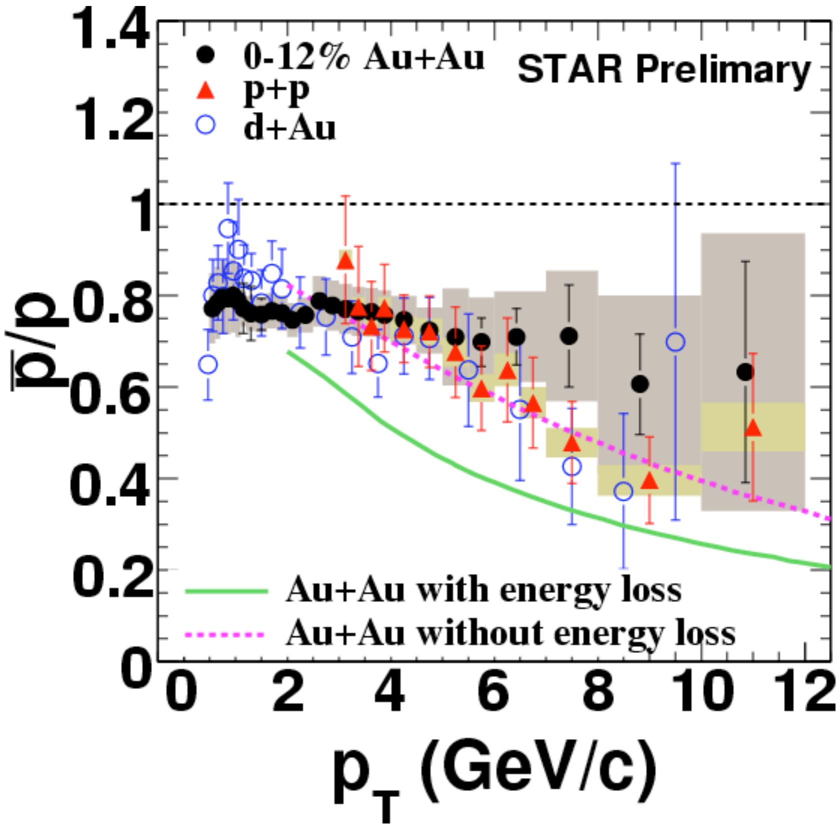
By the way!

Take a second look at the anti-proton/proton ratio

$\bar{p}/p \sim 0.8$

There is a net baryon number at mid-rapidity!!

Baryons number is being transported over 6 units of rapidity from the incoming beams to the collision zone!



Baryon number not carried by quarks

- baryon junctions postulated

Evidence for thermalization?

- Not all processes which lead to multi-particle production are thermal - elementary collisions

- *Any* mechanism for producing hadrons which evenly populates the free particle phase space will mimic a microcanonical ensemble.

- Relative probability to find n particles is the ratio of the phase-space volumes $P_n/P_{n'} = \varphi_n(E)/\varphi_{n'}(E)$ ⇒ given by statistics only.

- Difference between MCE and CE vanishes as the size of the system N increases.

- Such a system is NOT in thermal equilibrium - to thermalize need interactions/re-scattering

Need to look for other evidence of collective motion

Determining the temperature

1/Wavelength ∝ Freq ∝ E ∝ p

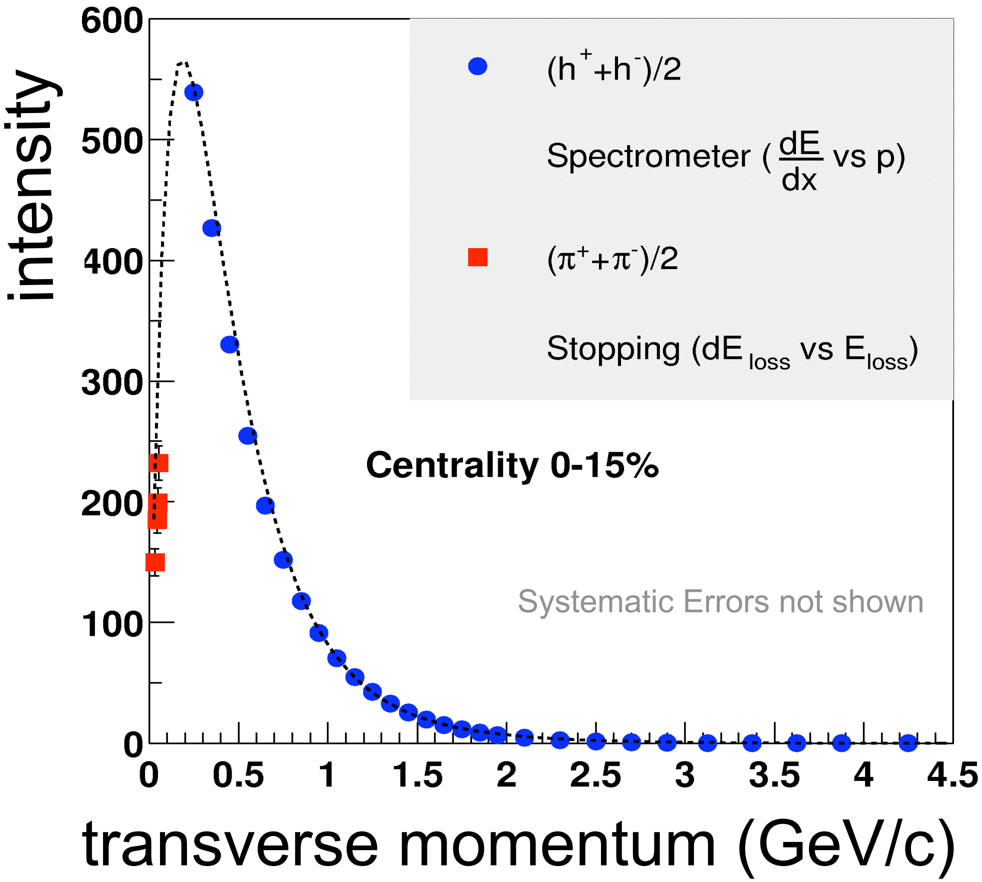
From transverse momentum distribution of pions deduce temperature ~120 MeV

$$E = \frac{3}{2}kT$$

$$T = \frac{2E}{3k}$$

$$= \frac{2 \times 120 \times 10^6}{3 \times 1.4 \times 10^{-23}} \times 1.6 \times 10^{-19}$$

$$\sim 9 \times 10^{11} K$$



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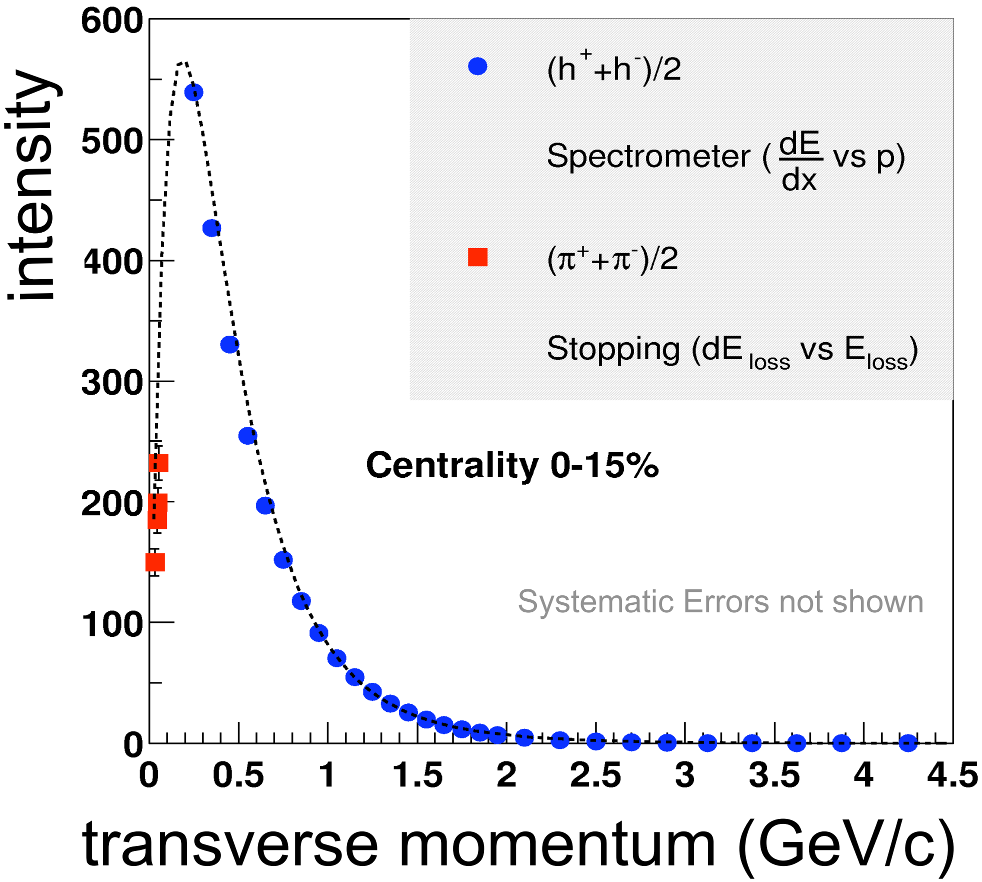
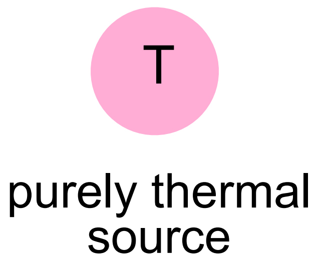
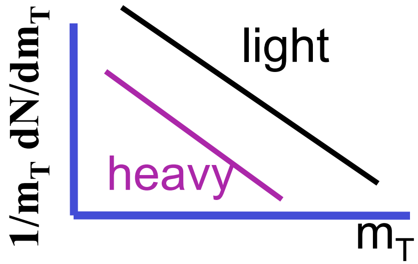


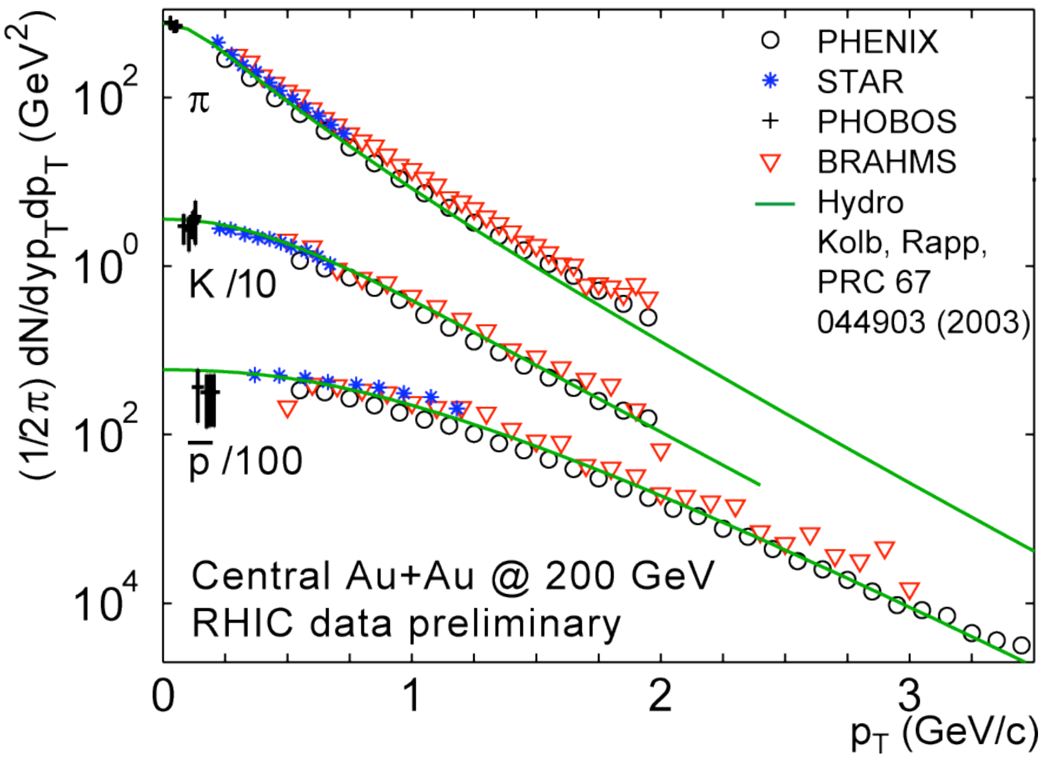
$T_{ch} > T_{fo}$

System exist for time in hadronic phase

Strong collective radial expansion







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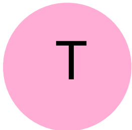
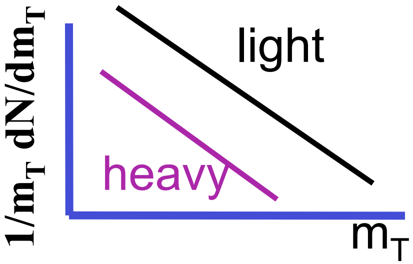
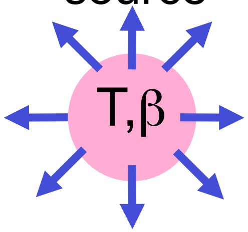
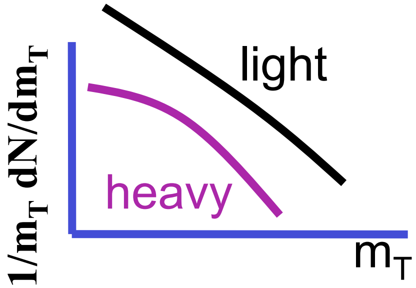




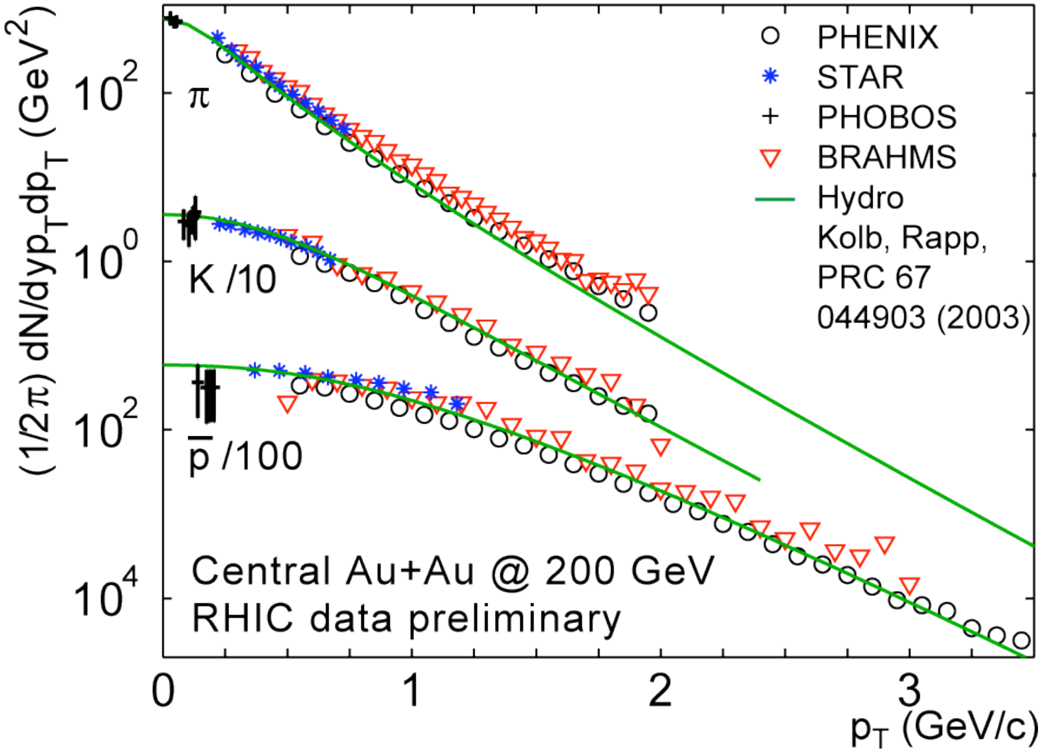
purely thermal source

explosive source



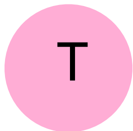


$m_T = (p_T^2 + m^2)^{½}$



- Different spectral shapes for particles of differing mass → strong collective radial flow

Strong collective radial expansion



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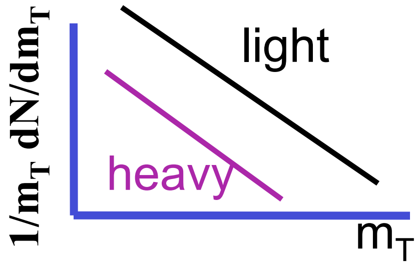

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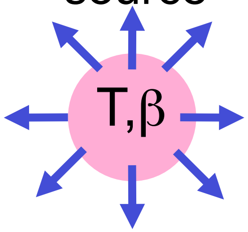

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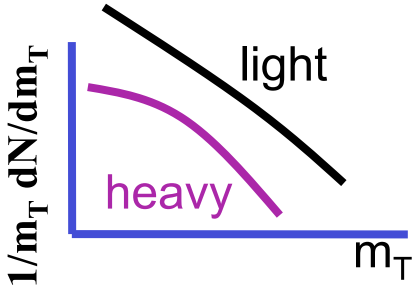
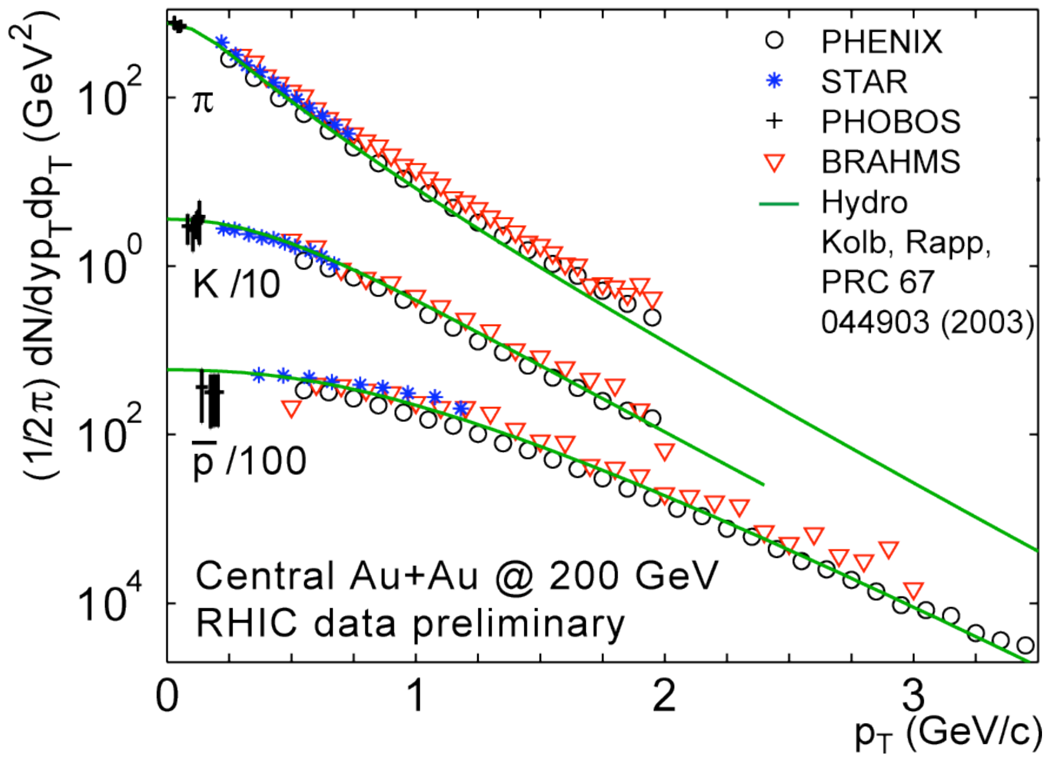




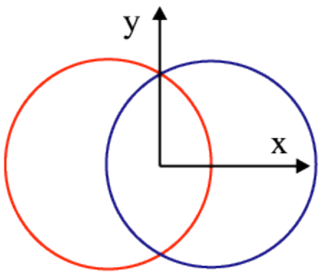
T_{fo}~ 100 MeV

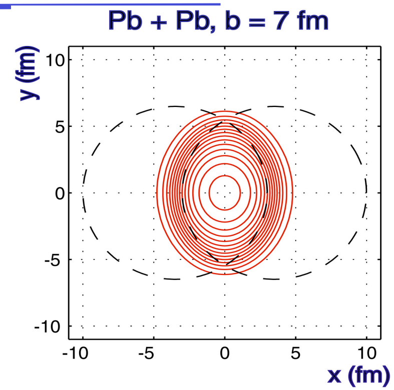
$\langle \beta_T \rangle$ ~ 0.55 c

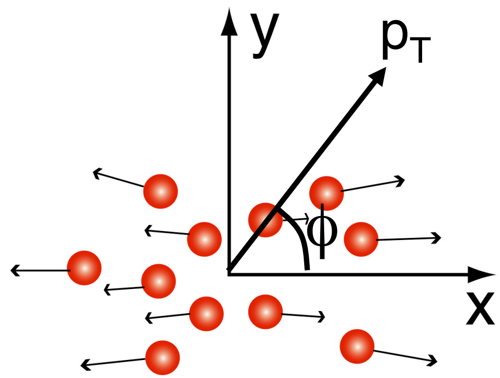
- Different spectral shapes for particles of differing mass → strong collective radial flow

Good agreement with hydrodynamic prediction for soft EOS (QGP+HG)

Anisotropic/Elliptic flow





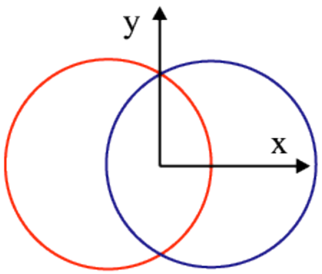


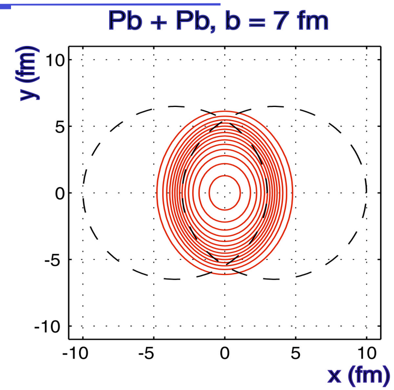
Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

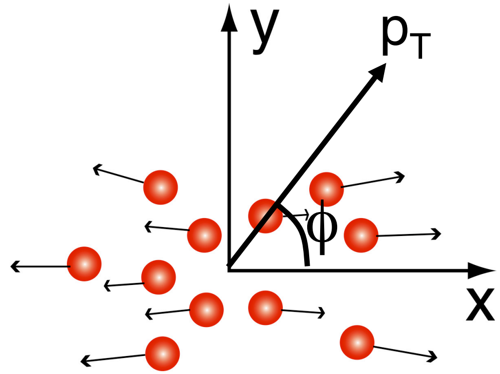
$dN/d\phi \sim 1+2\, v_2(p_T)\cos(2\phi) + \ldots.$ $\phi=\mathrm{atan}(p_y/p_x)$ $v_2 = \langle\cos 2\phi\rangle$

v_2: 2nd harmonic Fourier coefficient in $dN/d\phi$ with respect to the reaction plane

Anisotropic/Elliptic flow







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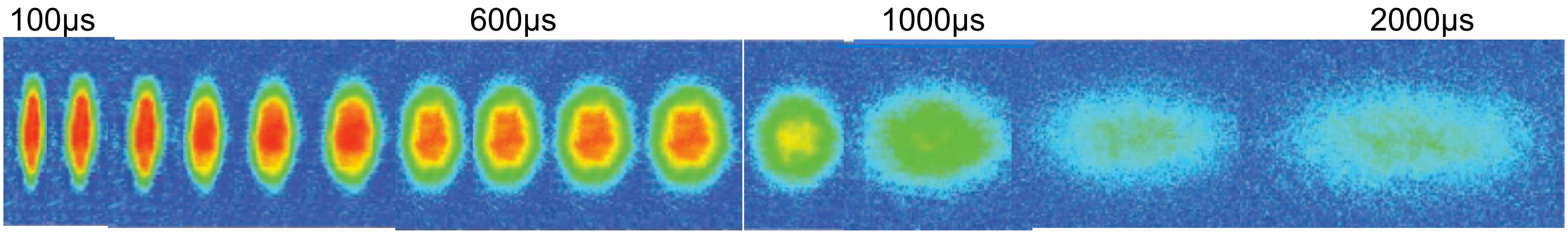
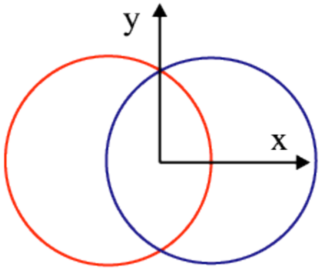
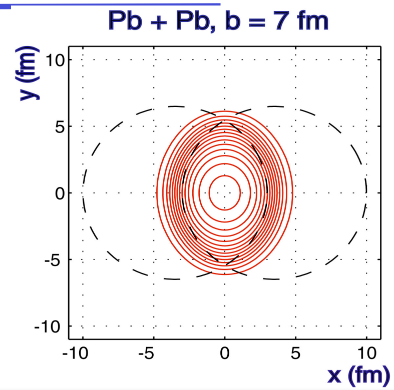


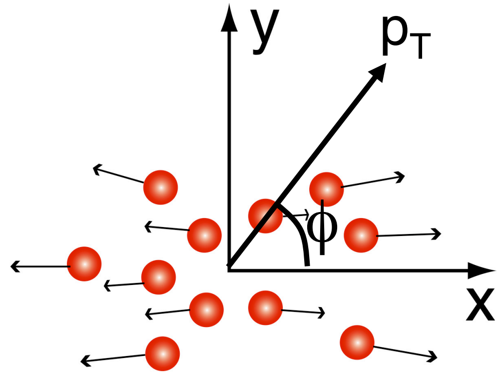
Time

–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Anisotropic/Elliptic flow





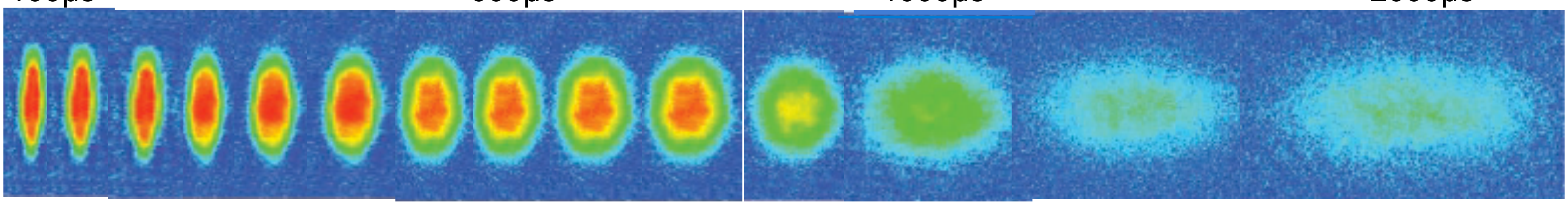


Elliptic flow observable sensitive to early evolution of system

Mechanism is self-quenching

Large v_2 is an indication of ***early*** thermalization

100µs 600µs 1000µs 2000µs



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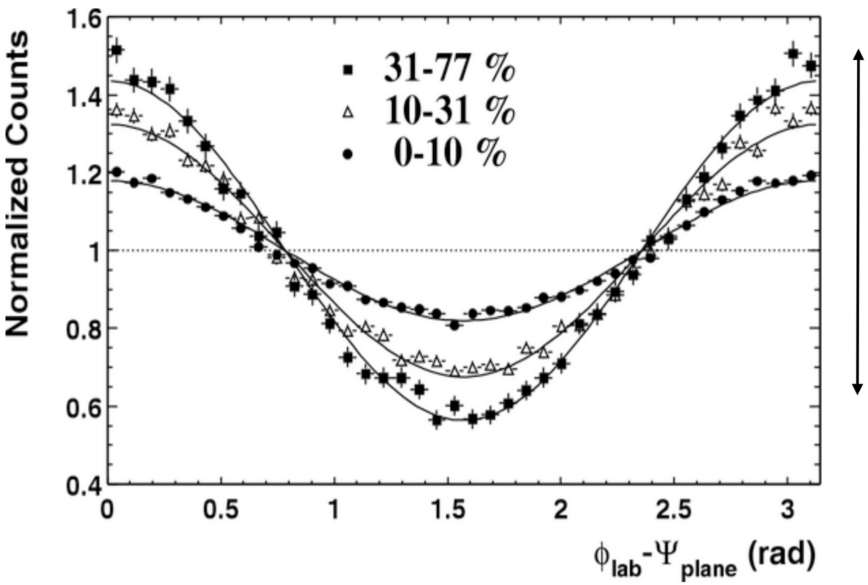
Elliptic flow

Distribution of particles with respect to event plane, $\phi-\psi$, p_t>2 GeV; STAR PRL 90 (2003) 032301



- Very strong elliptic flow → early equilibration

Factor 3:1 peak to valley

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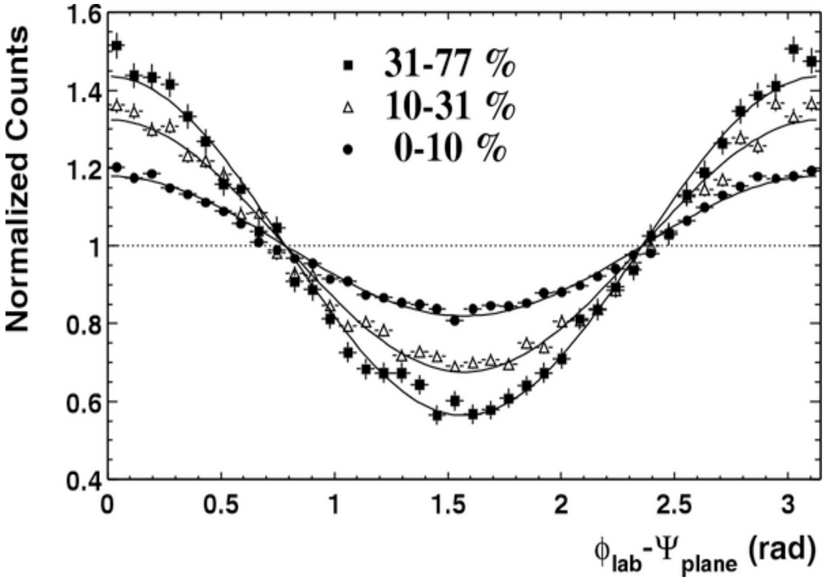
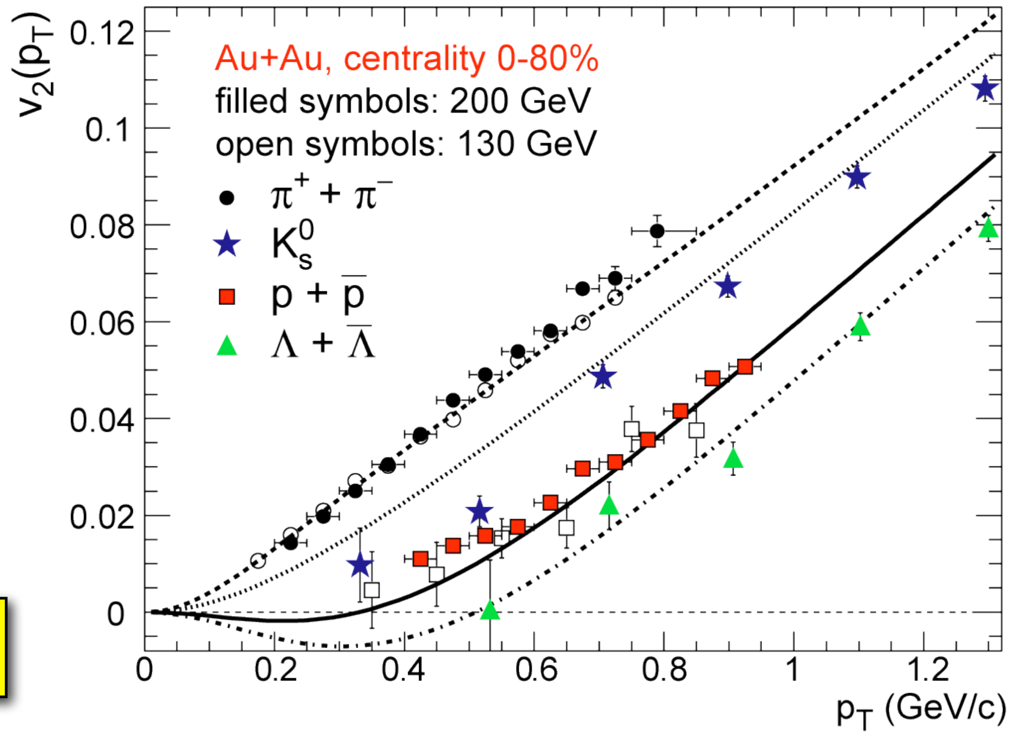


- Very strong elliptic flow → early equilibration

Factor 3:1 peak to valley

- Pure hydrodynamical models including QGP phase describe elliptic and radial flow for many species



QGP→ almost perfect fluid

Just a gas of hadrons?

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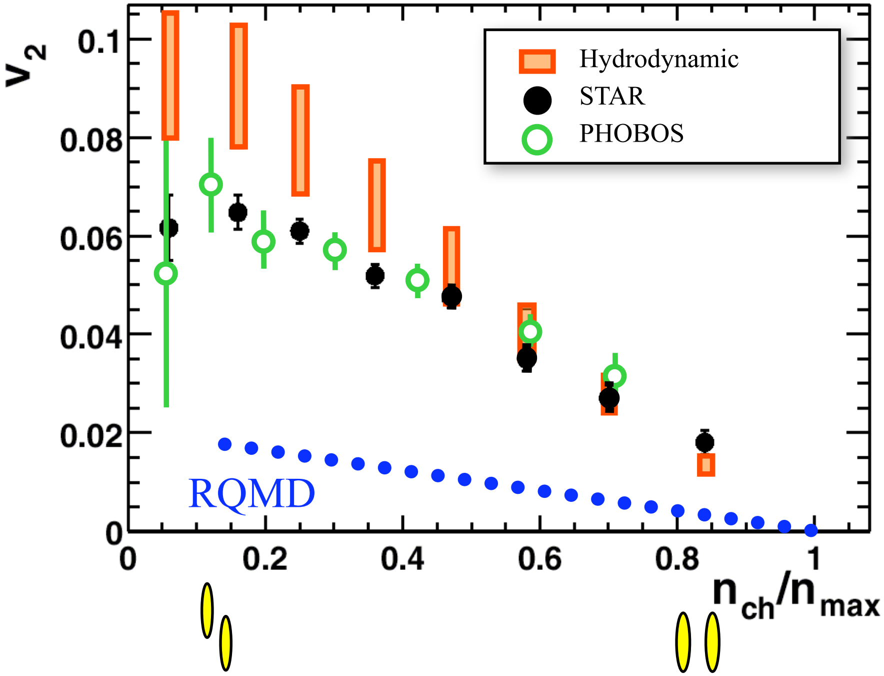
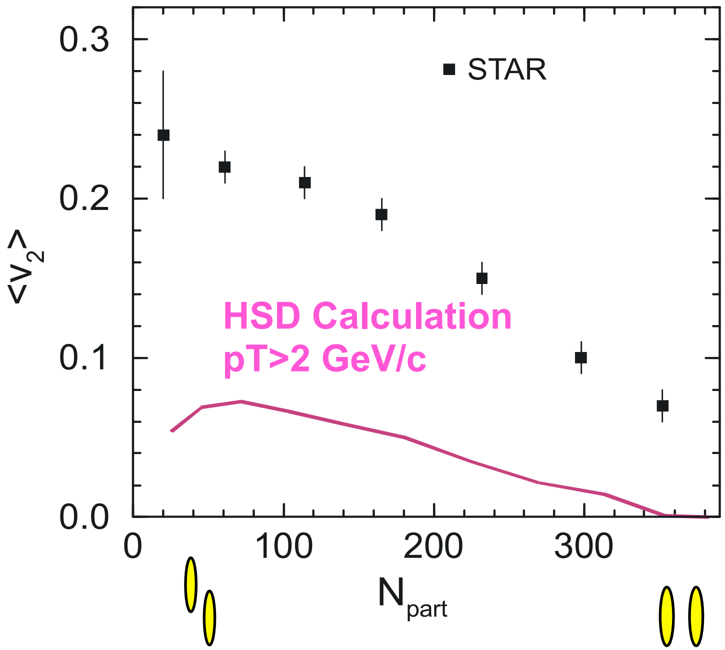
Hadronic transport models (e.g. RQMD, HSD, ...) with hadron formation times ~1 fm/c, fail to describe data.





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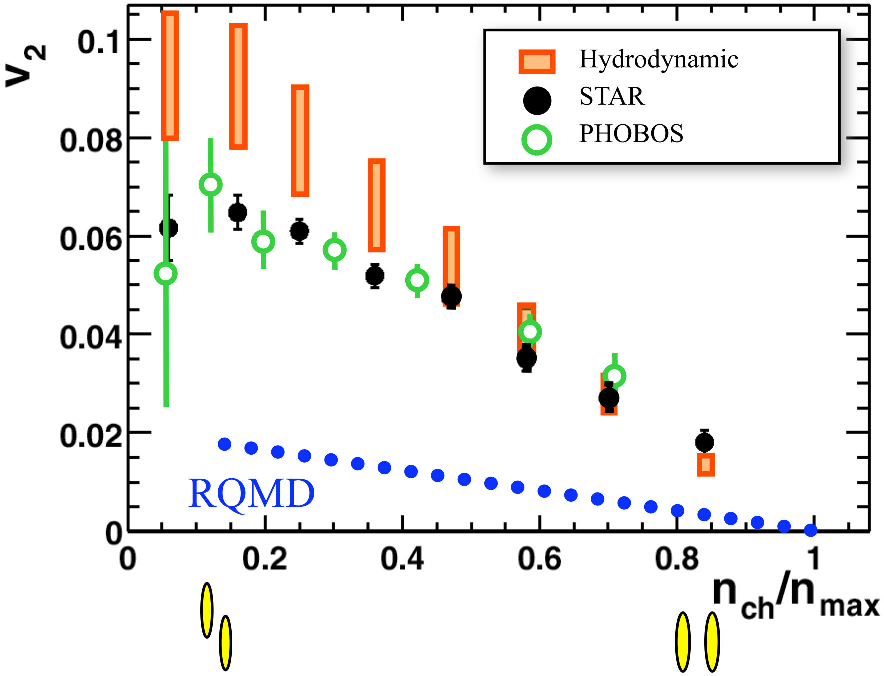

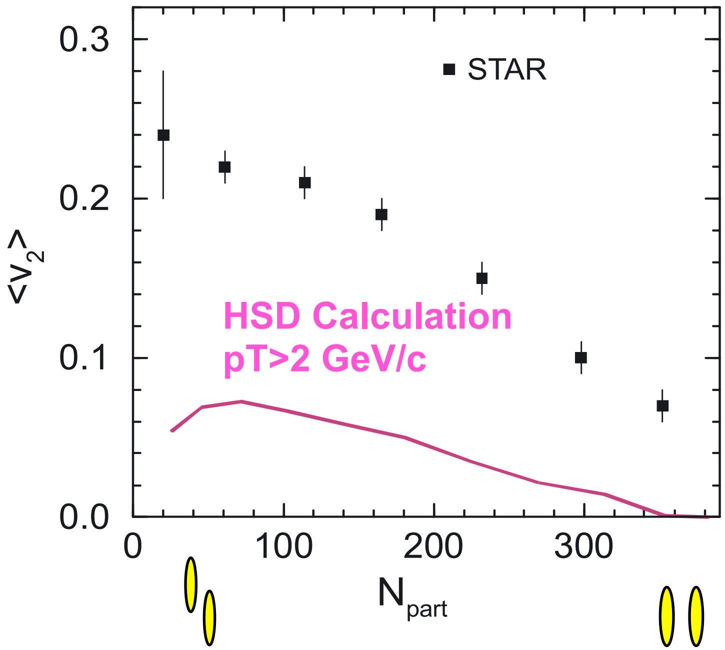

Clearly the system is not a hadron gas. Not surprising.

Just a gas of hadrons?

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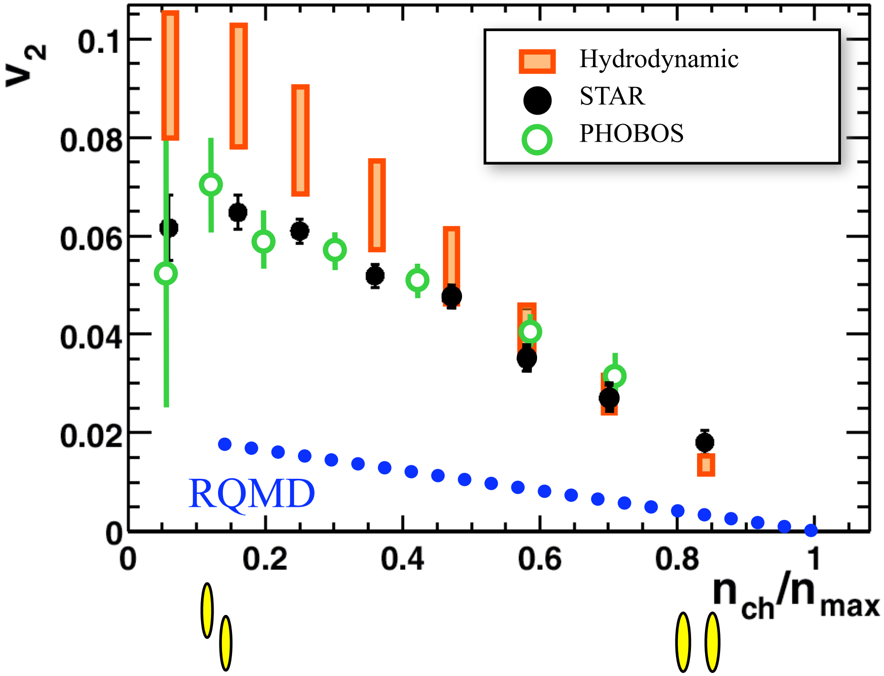

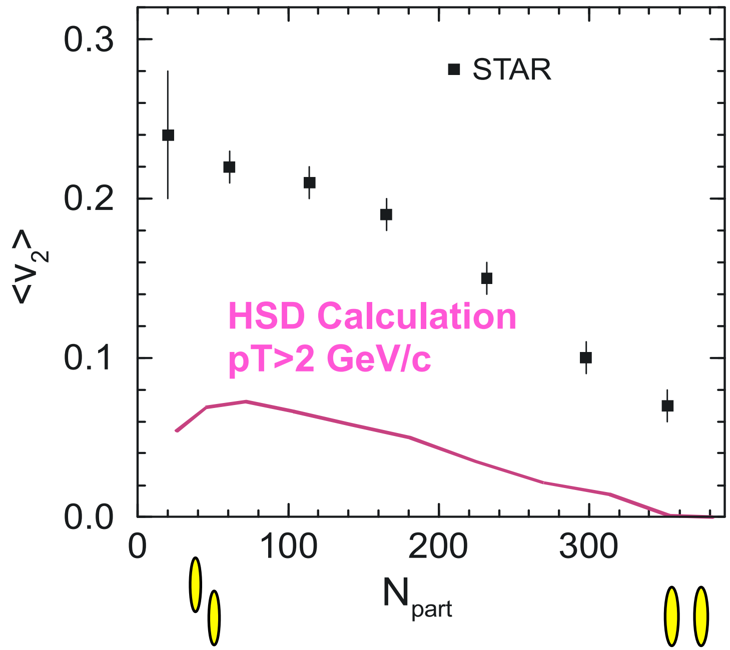

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Hydrodynamical calculations:thermalization time t=0.6 fm/c

What interactions can lead to equilibration in < 1 fm/c?

The constituents "flow"

- Elliptic flow is additive.
- If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2\, v_2(p_T)\cos(2\phi)$$

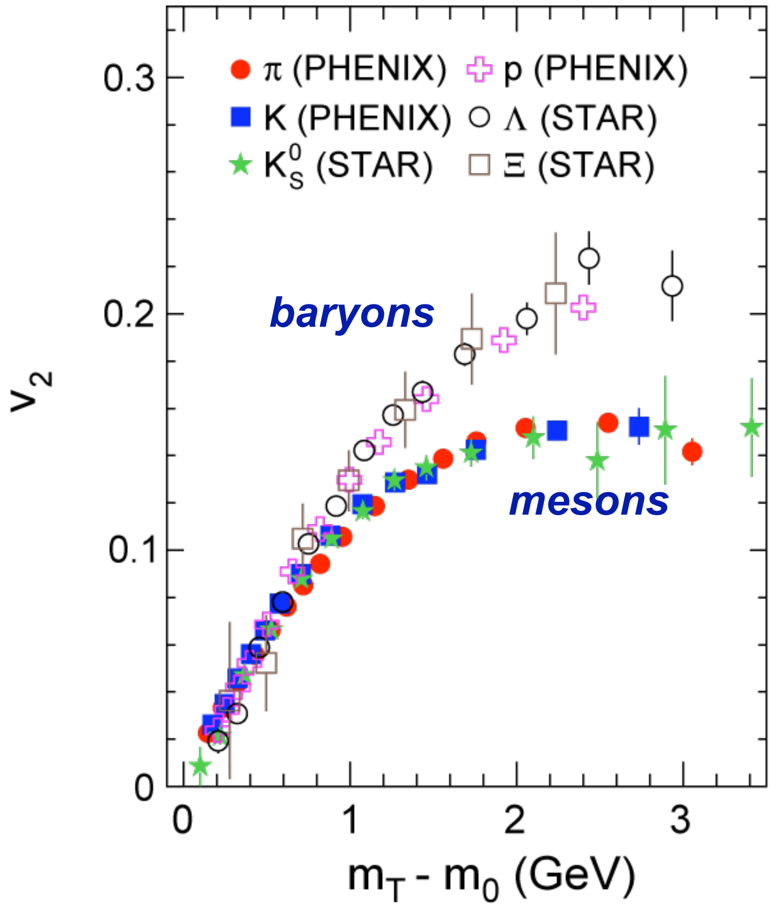
should become *simple* at the quark level

$p_T \rightarrow p_T / n$

$v_2 \rightarrow v_2 / n$,

n = (2, 3) for (meson, baryon)

$$m_T = \sqrt{p_T^2 + m_0^2}$$



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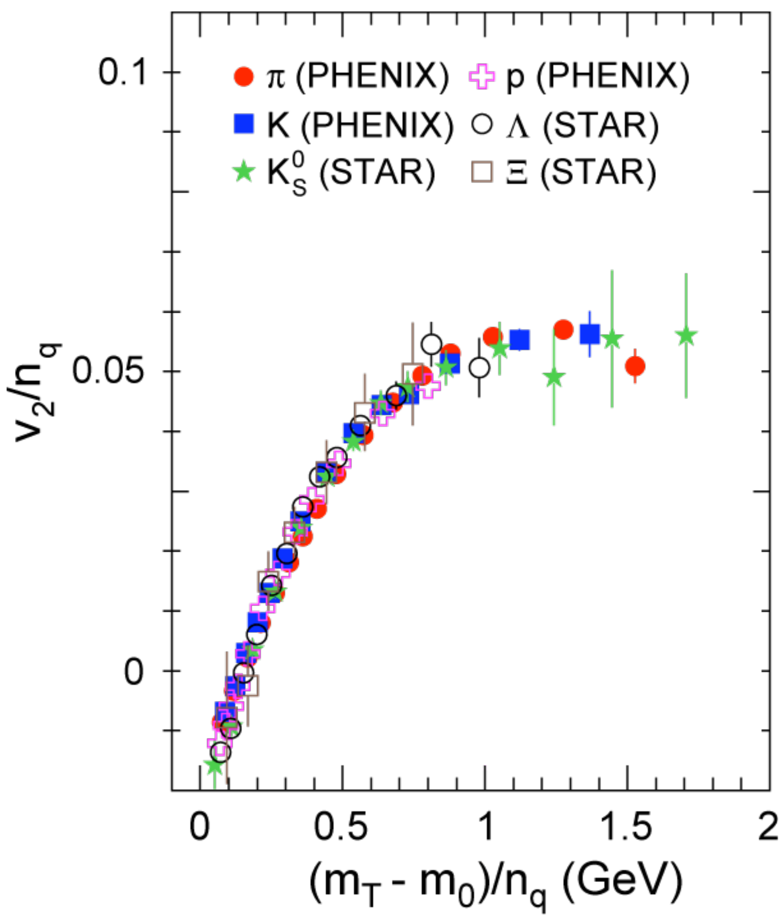
Works for p, π, K^0_s, Λ, Ξ..

$v_2^s \sim v_2^{u,d} \sim 7\%$

$$m_T = \sqrt{p_T^2 + m_0^2}$$



Constituents of QGP are partons

Summary of what we learned so far

- Energy density in the collision region is way above that where hadrons can exist

- The initial temperature of collision region is way above that where hadrons can exist

- The medium has quark and gluon degrees of freedom in initial stages

We have created a new state of matter at RHIC - the QGP

- The QGP is flowing like an almost "perfect" liquid